

A Primer on the Detection of Nuclear and Radiological Weapons

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Executive Summary

Terrorist use of radioactive nuclear materials is a serious threat for mass destruction or disruption of civil and military activities. Most worrisome is the use of nuclear devices to cause massive casualties to people and damage to structures. Fortunately, the procurement of adequate material and the engineering design, construction, and transportation and triggering of a nuclear weapon are all difficult problems for terrorist organizations. More likely is a device that combines radioactive materials with conventional explosives to make a radiological dispersion device, commonly called a "dirty bomb". The procurement of nuclear materials for this purpose, the construction of the bomb and its use are all easier than for a nuclear weapon. Fortunately, the effects from the use of a radiological weapon would be much smaller than from a nuclear device, although they could still be very disruptive. Thus, it is important to detect the transport of nuclear weapons and radiological dispersion devices and the materials for their construction. These materials emit gamma rays or neutrons, which can be detected to show the presence and amounts of such materials.

Radiation detectors have two applications toward nuclear and radiological weapons of mass destruction. The first is to intercept nuclear materials and devices prior to a terrorist attack. The second is for assessment and attribution after an attack. Such detectors represent relatively mature technologies. Portable radiation instruments were developed over fifty years ago in response to the use of nuclear weapons in WW II. Modern electronics and detector materials have made them much more capable. Now, new materials are being developed to enable even more efficient detection of gamma rays and neutrons with simpler devices. In recent years, large systems for imaging of gamma rays from nuclear materials and devices have been developed. Many passive and active, fixed and portable instruments for the detection of gamma rays or neutrons are available commercially.

Geometry, air attenuation, and background radiation from natural and man-made sources determine the limits of detection of these materials. For realistic source strengths and available gamma-ray and neutron detectors, nuclear materials and devices can be detected at ranges of a few meters up to a few tens of meters, at most. Detection from fixed-wing aircraft or satellites is impossible. Examples of detection limits for generic detectors are given in this report. It is necessary to quantify the limits of utility for specific nuclear radiation detectors under the circumstances in which they are likely to be used.

1. Introduction

The detection of materials or devices for nuclear or radiological weapons of mass destruction (NRWMD) is fundamentally important to both homeland security and to military operations. Detection technologies are necessary both to find and to verify the location of materials, components, and systems for NRWMD. They are also central to actions taken after deployment of a NRWMD. The study upon which this report is based was undertaken because of the large and growing importance of detection technologies for NRWMD. While this report will focus on detection of NRWMD, the NRWMD problem does not have a purely technical solution. The reasons for this will become clear in this report. Detectors are necessary but not sufficient for dealing with this problem.

This report seeks to be pragmatically comprehensive in its coverage. It takes a level intermediate between policy, on one hand, and technology details, on the other hand. The goal is to provide part of the basis for “higher level” policy considerations, as well as a framework for “lower level,” more detailed technical concerns. Readers of this report are expected to fall into a few classes. They include policymakers, managers responsible for implementing policies and putting in place the combinations of technologies and people for effective and timely detection of NRWMD materials and devices, users of the technologies, technology developers, and students. This report presents the fundamentals of detection technologies and insights into the current and coming state-of-the-art in such technologies. As such, it should be of use to most of these readers. Researchers involved in developing new technologies will not find the latest details of their field documented in this report, since this is not a scientific review article. However, researchers might find this overview of the technologies of interest.

The detection of NRWMD shares many features of the more general case of the detection of WMD. The variety of materials and devices relevant to defense against WMD can be arrayed against the diverse detection

technologies to form a two-dimensional matrix. It would show that (a) multiple detection technologies are relevant to most of the different WMD materials and devices, and (b) a given detection technology can be used to detect more than one kind of WMD material or device. However, such a spreadsheet is insufficient to describe the complexity of the overall field. This is the case because any combination of one material or device with one detection technology can be used in a variety of scenarios. For example, security at ports dealing with the contents of arriving containers is radically different than the actions of first responders coming on the scene of an urban radiological emergency. Hence, we are really concerned with a quasi three-dimensional space, such as that sketched in figure 1. Some boxes in the plane relating WMD and detection technologies are not relevant. That is, some detection

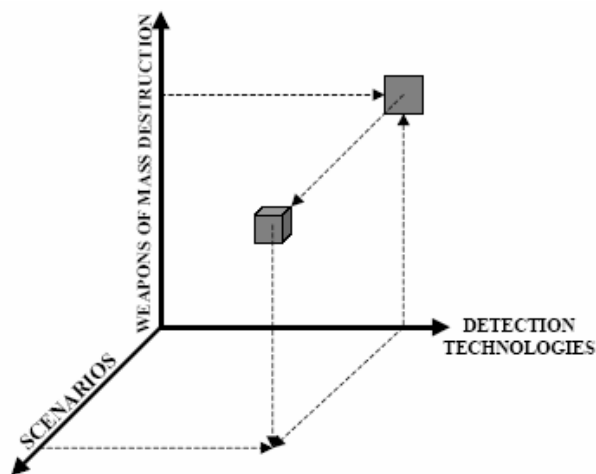


Figure 1. Schematic of the three-dimensional “space” defined by different WMD subjected to various detection technologies in a variety of employment scenarios.

instruments do not apply to some WMD materials and devices. Even those that are relevant do not come into play in all scenarios. However, there are indeed many combinations of the three factors that are significant. Hence, the detection of WMD materials is complex due to its variety as well as because of technical and practical factors.

Detection technologies provide information that has various uses. Very often the output of an instrument is locally and immediately useful. An example is the detection of an explosive material in the backpack of a person seeking admission to a political convention. Other times, the information from an instrument for detecting WMD materials is used remotely as a basis of action. The latter situation will be increasingly relevant as responsible officials employ distributions of diverse manned and unmanned sensors to obtain larger area views of complex scenarios. The release of a radiological material in the heart of a city would be an example. In such cases, simulations of the expected flow for the prevailing wind conditions might be used to provide brief, but crucial, warnings to people downwind from the release. Figure 2 sketches the sequences of actions in such cases. Information from the detection is combined with simulations under various scenarios. The results are communicated to decision makers who determine appropriate actions. The detection technologies themselves are but a part of a much more complex undertaking.

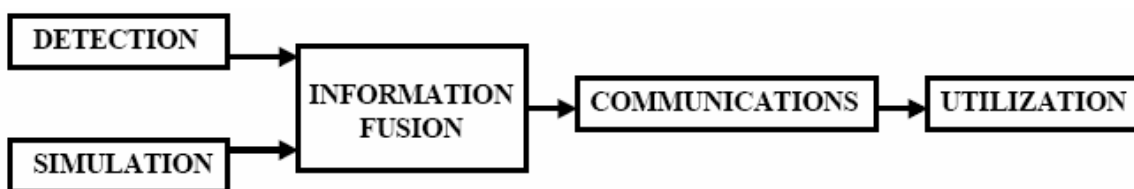


Figure 2. Illustration of the generation, fusion, and utilization of information from detection and simulation technologies.

This study was motivated by increases around the world in the frequency of terrorist attacks and by the importance of WMD, in general, as asymmetric weapons, which can have impacts very disproportionate to their costs. These events and factors come at a time when technologies, generally, and detection technologies, specifically, are improving with unprecedented rapidity. Advances in diverse miniaturization technologies, including micro-electronics, -magnetics, -optics and -mechanics, are being applied to detection instrumentation.

There are many technologies for the detection of people and vehicles that might be transporting materials or devices for WMD. They exploit acoustic, seismic, optical, radio-frequency and other mechanisms, which indirectly provide information on WMD. While such non-specific technologies can be very important for overall defense against WMD, they are not within the scope of this report, which focuses on technologies that can directly detect the materials or devices that might become, or are already part of, a WMD.

Section 2 describes nuclear radiations and how they interact with matter, including detectors. The effects of nuclear explosions and the effects of radiation on people are surveyed in Section 3. Section 4 briefly describes the design of nuclear weapons and details the observable radiations from nuclear weapons and nuclear materials. This section includes a discussion of the effects of radiological weapons or “dirty bombs” and the observable radiations from radiological materials. Section 5 focuses on the background radiation from gamma rays, cosmic rays, and neutrons, which often determines detection thresholds. It goes on to discuss the challenges of weapons

detection in the natural radiation environment. Section 6 gives a general discussion of radiation detectors and detector deployment scenarios as background for the following material. Section 7 reviews available point detector technologies for gamma rays and neutrons, and Section 8 surveys imaging technologies. Section 9 discusses new detector technologies in development and new integrated detection systems. The concluding Section 10 summarizes the major characteristics and useful ranges of detectors for nuclear and radiological weapons. Appendix A provides a unified view of the calibration curves and receiver operating characteristics that determine detector performance. Appendix B summarizes the practical aspects of nuclear radiation detectors, and includes a check list for managers making procurement decisions.

2. Nuclear Radiation and Interactions

All nuclear detection technologies are designed to detect emissions from the decay of radioactive nuclides, which can occur naturally, such as uranium and thorium, or are manmade, such as plutonium and various fission products produced in a nuclear reactor. The French physicist Henri Becquerel discovered radioactivity in 1896, when he observed images on photographic plates wrapped in black paper and exposed to uranium. For this, he shared the first Nobel Prize in Physics 1903. Following Becquerel's discovery, early investigators identified three types of radioactivity which they called α , β and γ rays. Alpha particles were found to be ^4He nuclei, consisting of two protons and two neutrons tightly bound. Beta particles can be either positively or negatively charged. The β^- was eventually identified as the common electron and the β^+ as its anti-particle, the positron. Gamma rays were found to be energetic photons. To these three emissions one can add x-rays and neutrons. X-rays and gamma rays are both high-energy photons, with gamma rays emitted during the decay of radioactive nuclei and x-rays during the realignment of atomic electrons following radioactive decay or by an electron beam striking a target. Neutrons are emitted during spontaneous fission by uranium and plutonium.

The primary long-range observables from nuclear materials are gamma rays and neutrons, which have mean free paths of the order of a hundred meters in air and only 10 cm in water (table 1). Alpha particles have a short range of about 50 mm in air but only about 60 μm in water. Beta particles have a range of a few meters in air, but are stopped by a few mm of water. X-rays and gamma rays have overlapping energy ranges of a few hundred eV to about 100 keV for x-rays and tens of keV to several MeV for gamma rays^a. Both are strongly attenuated by high atomic number materials, such as lead.

^a The electron volt (eV) is the energy gained by an electron when accelerated through a 1 volt potential. Energies of gamma rays and other nuclear particles are commonly given in keV (10^3 eV) or MeV (10^6 eV).

Table 1. Range of Nuclear Particles

	<i>energy (keV)</i>	<i>range (m)</i>			
		<i>in air</i>	<i>in water</i>	<i>in aluminum</i>	<i>in lead</i>
alpha particles	5000	0.05	6×10^{-5}	3×10^{-5}	2×10^{-5}
beta particles	1000	4	0.004	0.002	7×10^{-4}
x-rays	10	1.9	0.002	1.4×10^{-4}	7×10^{-6}
	30	30	0.03	0.004	3×10^{-5}
	100	50	0.06	0.02	1.7×10^{-4}
gamma rays ^a	400	80	0.09	0.04	0.004
	1000	120	0.14	0.06	0.013
	1000	200	0.10	0.10	0.08
neutrons ^b					

References: [Attix, 1976; Lamarsh, 1975; NIST, 2003]

In addition to attenuation, the signal from a point source of radiation decreases with an inverse square geometrical dependence with distance. The detection range of nuclear materials is also limited by interference of the background radiation due to man-made and naturally occurring radionuclides and to cosmic rays. Nuclear materials near the earth's surface are not observable from high-flying aircraft or from satellites, despite occasional claims to the contrary.

The fissile nuclides, ^{235}U and ^{239}Pu , in subcritical mass amounts, decay primarily by alpha particle emissions followed by gamma rays and x-rays. This results in a chain of unstable nuclei that build up and decay over time, leading eventually to lead. Some of the decay products emit gamma rays whose energies are characteristic signatures of the fissile material. There is also a small probability of spontaneous fission for ^{235}U and ^{239}Pu , resulting in emission of 2.5 to 3 energetic neutrons per fission. These fission neutrons can induce additional nuclei to fission leading to a chain reaction. A critical mass is the amount of fissionable material just necessary for a self-sustaining nuclear chain reaction, as occurs in a nuclear reactor. Rapid assembly of a supercritical mass results in a nuclear explosion. Weapons grade plutonium typically contains 6% of the ^{240}Pu nuclide, which has a relatively high spontaneous fission probability resulting in significant neutron emission, but which reduces the efficiency for a nuclear explosion.

Industrial radionuclide sources of gamma rays include ^{137}Cs and ^{60}Co . Industrial neutron sources include ^{252}Cf and $^{241}\text{Am/Be}$. Linear accelerators are also used to produce neutrons or high-energy x-rays. Unlike sources, they have the advantage that they are emission free when powered down. Some of these accelerators are small enough to be considered portable or transportable.

Fission neutrons from ^{235}U and ^{239}Pu have an average energy of about 1 MeV. At these energies, measured neutron attenuation lengths in most solids range from 6 to 10 cm [Attix, 1976; Lamarsh, 1975]. To shield against these, a moderator is used in which the fast neutrons slow down primarily by elastic scattering. This is usually combined with a material with a high capture rate for "thermal" neutrons (neutrons which have slowed down until their energies are in equilibrium with the thermal environment, about 0.025 eV.) It takes a large number of scatterings to slow down a fast neutron to thermal energies, so that it can be absorbed or

^a X-rays and gamma rays do not have a well-defined range. The table gives the average attenuation length or mean free path.

^b The table gives the measured attenuation length for fission energy neutrons.

“captured.” The most effective moderators are those with high hydrogen content such as water, paraffin or polyethylene. Graphite is also used as a moderator in some reactors. The mean distance to slow down fission energy neutrons to thermal energies is about 12 cm in polyethylene, 13 cm in water and 47 cm in graphite [Lamarsh, 1975]. Materials with high thermal neutron capture probabilities include ^3He , ^6Li , ^{10}B , ^{113}Cd and ^{157}Gd . After capture, energetic electrons or heavy charged particles (protons, alphas, etc.) are emitted, which can be detected by a particle detector.

3. Nuclear and Radiation Effects

A. Effects of Nuclear Weapons

Nuclear weapons have the greatest destructive potential of all weapons of mass destruction. The 20-kiloton (kT) bomb dropped on Hiroshima (figure 3) destroyed almost everything out to a radius of one mile (1.6 km) [Manhattan, 1946]. An unshielded person exposed to the radiation from a 20-kT burst would receive a lethal dose exceeding 10 Gy^a out to about 1.2 km, about equally due to gamma rays and neutrons [Glasstone, 1977]. Because both are strongly attenuated by a few hundred meters of air, a factor of a thousand increase in yield only extends the lethal dose radius by about a factor of two; a 20-MT thermonuclear explosion would deliver a lethal dose out to about 3.0 km. A study by the Congressional Office of Technology Assessment of the effects of a 25 MT blast over Detroit estimated about 3.2 million casualties and 1.8 million deaths and predicted serious structural damage out to a radius of 11 km [OTA, 1979]. Fallout, while highly variable depending on local weather conditions, would likely extend to much greater distances. The early (first day) fallout pattern from a 20-MT surface burst, for a wind speed of 24 km/hr, would cut a swath producing a dose rate of 10 mGy/hr or greater downwind for a distance of 245 km and with a maximum width of 20 km [Glasstone, 1977].

^a The International System (SI) unit of dose is the gray (Gy) defined as the energy deposition of one J/kg. The sievert (Sv) is the equivalent dose adjusted for biological effects. (Neutrons have a biological effect about 10 times that of gamma rays.) Still in use are the older units, the rad = 0.01 Gy and the rem = 0.01 Sv.



Figure 3. Ruins of Hiroshima [Papalia, 2003].

B. Human Effects of Radiation

The effects of radiation on people can be divided into a) acute physical effects, which occur at high doses and lead to debilitation or death, and b) longer-term, low-dose effects, such as cancer and genetic effects, which lead to birth defects in offspring. The effects of acute doses vary widely depending on the organs exposed. Doses as low as 0.1 Gy (10 rad) to the testes can cause temporary sterility in men. Doses of 0.5 to 2 Gy to the eye can lead to an increase in cataracts. Red bone marrow is affected by doses as low as 0.5 Gy, but the damage at these dose levels is usually reversible. Higher doses of 3-5 Gy result in 50% mortality after 1 to 2 months due to bone marrow damage. Doses of 10 to 50 Gy kill within 1 to 2 weeks due to gastrointestinal damage, while doses of 100 Gy kill in a few hours or days due to nervous system damage [UN, 1986].

Biological effects vary greatly depending on the type of radiation. Short-range alpha particles are stopped by the dead skin layer, where they are not harmful. However, when ingested or inhaled they can cause leukemia or lung cancer. Beta radiation can penetrate several mm of skin and cause painful burns. The more penetrating gamma rays and neutrons can damage internal organs at high doses. The average background dose to people in the U.S. is about 2 mSv per year. Medical x-rays add another 0.4 mSv on average.

There is little data on hereditary effects of radiation. Extrapolating from high-dose survivors of the atomic bombs dropped on Hiroshima and Nagasaki in Japan, the UN estimates an eventual increase in birth defects of about 1.5% for a cumulative population dose of 1 Gy per generation. Cancer risks have proven even harder to quantify. The incidence of leukemia peaked at about 6 years in the atomic bomb survivors, while the rates of all other cancers rose slowly and peaked much later at about 30 years. There is little data available on the effects of much lower doses

received by the general population, and little agreement on the validity of extrapolating from the high-dose effects seen in survivors of the nuclear explosions.

The U.S. annual regulatory exposure limit for radiation workers is 0.05 Sv. The limit for exposure to the general public is 5 mSv.

4. Characteristics of Nuclear and Radiological Weapons

A. Nuclear Weapons

The first types of nuclear weapons developed during WWII were fission weapons relying on the sudden assembly of a supercritical mass of ^{235}U or ^{239}Pu . Two methods can be used to achieve this: a) gun assembly where an explosive charge is used to propel two subcritical masses together into a supercritical mass, and b) implosion, where a shaped charge is used to compress a subcritical mass into a supercritical condition (figure 4). Modern fission weapons are almost all of the implosion type. This results in explosions with yields in the range of 1 kiloton (kT) to hundreds of kilotons of TNT equivalent.

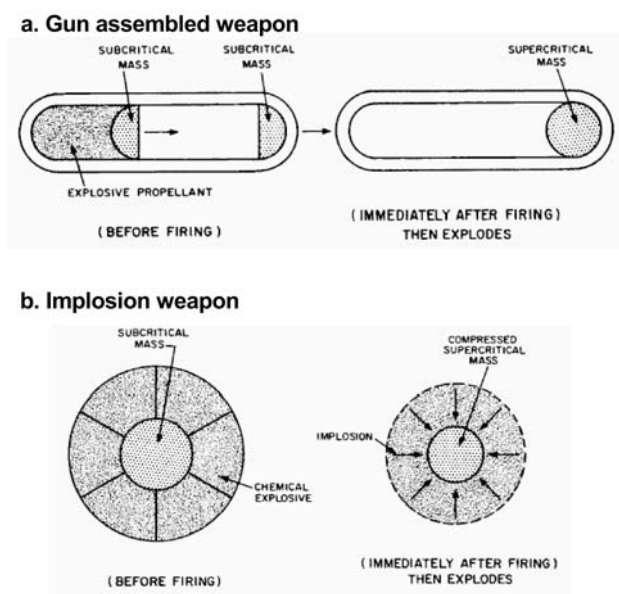


Figure 4. a.) Diagram of a gun assembled weapon. b.) Diagram of an implosion weapon [Glasstone, 1977].

Thermonuclear fusion weapons, first developed in the 1950's, rely on a first stage fission explosion to provide the energy needed to trigger a second thermonuclear stage. The second stage makes use of high pressure and energy from the fission explosion to initiate the fusion of deuterium or lithium, resulting in the release of large amounts of energy with explosive yields in the 1- to 100-megaton (MT) range. Detection of the transport of either type of weapon depends on detecting high-energy gamma rays or neutrons emitted by the fission fuel. More details on nuclear weapon design can be found in [FAS, 1998].

B. Nuclear Weapon Materials

Two fissile materials, ^{235}U and ^{239}Pu , which are fissionable by neutrons of all energies, are commonly used in nuclear weapons. Natural uranium contains only 0.7% of fissile ^{235}U and is mostly (99.3%) ^{238}U , which is fissionable only by high-energy neutrons. For a fission weapon, uranium must be enriched to about 93% ^{235}U . This is known as weapons grade uranium (WGU) or highly enriched uranium (HEU). If natural uranium is used as the feedstock for enrichment, the remaining 7% will be ^{238}U . However, if reprocessed uranium from a reactor is used, there will be small amounts of other uranium isotopes, one of which, ^{232}U , has decay products that build up over several years and are strong gamma-ray emitters. After enrichment, the natural uranium feedstock is reduced to less than 0.3% ^{235}U . This material, known as depleted uranium (DU), thus contains greater than 99.7% ^{238}U . DU by itself is not fissile but it is often found in fission weapons as a tamper, which acts to prevent premature expansion and also to reflect neutrons back into the fissile material. DU is also employed as a radiation casing and fuel in thermonuclear weapons, where it is fissionable by high-energy neutrons from fusion. Because of its high density, DU is also used in heavy, armor-piercing munitions.

Weapons grade plutonium (WGPu) contains about 93% of the fissile nuclide ^{239}Pu , about 6% of ^{240}Pu and less than 1% of other isotopes. Most of the neutron activity of both WGU and WGPu is due not to the fissile isotopes but to the other isotopes contained in lesser amounts in the materials. Table 2 summarizes the composition and neutron activity from WGU and WGPu.

Table 2. Neutron Activities from Nuclear Materials

Weapons Grade Uranium Neutron Activity						
<i>mass number (A)</i>	<i>spontaneous fission half-life (years)</i>	<i>spontaneous fission neutron activity (n/kg/s)</i>	<i>alpha- induced activity (n/kg/s)</i>	<i>WGU composition</i>	<i>WGU neutron activity (n/kg/s)</i>	<i>percent activity</i>
234	1.50×10^{16}	9.43	50	1.0%	0.594	38.3%
235	1.00×10^{19}	0.01	0.012	93.3%	0.024	1.6%
238	8.20×10^{15}	16.95	0.001	5.5%	0.932	60.1%
other				< 0.2%		
Total activity					1.550	

Weapons Grade Plutonium Neutron Activity						
<i>mass number (A)</i>	<i>spontaneous fission half-life (years)</i>	<i>spontaneous fission neutron activity (n/kg/s)</i>	<i>alpha- induced activity (n/kg/s)</i>	<i>WGPu composition</i>	<i>WGPu neutron activity (n/kg/s)</i>	<i>percent activity</i>
238	4.75×10^{10}	2.93×10^6	2.20×10^5	0.005%	160	0.2%
239	8.00×10^{15}	17	630	93.3%	600	0.8%
240	1.14×10^{11}	1.21×10^6	2,300	6.0%	72,700	98.6%
241	6.00×10^{16}	2.3	22	0.4%	0.1	<0.01%
242	6.77×10^{10}	2.02×10^6	33	0.015%	300	0.4%
other				<0.2%		
Total activity					73,800	

References: [Browne, 1986], [Fetter, 1990], [Holden, 2000]

The dominant decay modes of the uranium and plutonium isotopes listed in table 2 are by alpha-particle emission, except for ^{241}Pu , which decays primarily by beta decay to ^{241}Am . The neutron activities arise mostly from spontaneous fissions, which have relatively long half-lives compared to alpha or beta emissions. In both uranium and plutonium, the spontaneous fission neutron activities are much greater for the even isotopes than for the odd isotopes. In some cases, alpha-particle reactions with light elements in the weapon (primarily carbon and oxygen) also result in significant neutron emissions [Fetter, 1990]. WGPu is a relatively strong neutron emitter, with most of the neutrons coming from ^{240}Pu . For this reason, plutonium weapons are generally much more easily detected than uranium weapons. In a hypothetical weapon design study using unclassified information [Fetter, 1990], a plutonium weapon containing 4 kg of WGPu with a 52 kg DU tamper was found to emit 400,000 neutrons per second. WGU emits very few neutrons, so the primary observables are low-energy gamma rays, which are easily shielded.

There has been some debate recently about whether a terrorist weapon could be made from reactor grade plutonium (RGPu), which tends to be less tightly guarded than WGPu [Mark, 1993]. RGPu has a higher percentage than WGPu of plutonium isotopes other than ^{239}Pu . It contains ^{240}Pu at a level of 10% or greater, which increases the neutron activity. A crude weapon made from RGPu could ignite prematurely due to the excess neutrons, resulting in a “fizzle” yield of only a few percent of the expected yield [CCNR, 1997]. Such an explosion would still spread highly radioactive material over a wide area with consequences similar to a “dirty bomb” as discussed in the following section.

A hypothetical uranium weapon design containing 12 kg of WGU surrounded by a 79 kg DU tamper would emit about 1,400 neutrons per second, while a tungsten tamper would reduce this to only 30 neutrons per second [Fetter, 1990]. Thermonuclear weapons with yields in the MT range use a fission first stage to trigger thermonuclear fusion in the second stage. Construction of a fusion weapon is probably beyond the technical capabilities of a terrorist group, but they could conceivably steal a poorly guarded one. In a thermonuclear weapon, the gamma-ray and neutron emissions from the fission fuel in the first stage may be significantly shielded and harder to detect, while the fusion fuel in the second stage consists of light elements, which do not emit detectable radiation. However, the second stage will also likely contain significant quantities of ^{238}U , which is used as a secondary fuel and is often used as an outer radiation casing. ^{238}U emits a penetrating 1001 keV gamma ray that is easily detectable and difficult to shield.

Table 3 lists the primary gamma-ray activities greater than 110 keV for each component of WGU. The most prominent gamma rays for each uranium isotope in the table are bolded. Gamma rays below 110 keV are easily shielded, and are also obscured by strong x-rays from uranium and its decay products. ^{235}U has a strong gamma ray at 186 keV. However, at this relatively low energy, it suffers from self-attenuation and is easily blocked by a few mm of lead. The 5-6% of ^{238}U in WGU has more penetrating, but relatively weak, gamma-ray emission at 1001 keV. Commonly, the most observable emissions from WGU are gamma rays from the small ^{232}U impurity, which is present in reprocessed uranium. Even assuming a ^{232}U composition as small as one part per million, the 239, 511, 583 and 2614 keV gamma rays from the ^{232}U decay chain are the strongest activities in the table, and they are difficult to shield due to their relatively high energies.

Table 3. Gamma-Ray Activities per Kilogram of Weapons Grade Uranium

(the most prominent gamma rays are bolded)

<i>mass number</i>	232^a		233		234		235		236		238^b	
<i>half-life (years)</i>	68.9		1.59x10 ⁰⁵		2.45x10 ⁰⁵		7.04x10 ⁰⁸		2.34x10 ⁰⁷		4.47x10 ⁰⁹	
<i>activity (Bq/kg)</i>	8.28x10 ¹⁴		3.57x10 ¹¹		2.30x10 ¹¹		8.00x10 ⁰⁷		2.39x10 ⁰⁹		1.24x10 ⁰⁷	
<i>WGU Composition^c</i>	0.0001%		0.01%		1.00%		93.30%		0.20%		5.50%	
	<i>energy (keV)</i>	<i>activity (kg-s)⁻¹</i>	<i>energy E(keV)</i>	<i>activity (kg-s)⁻¹</i>	<i>energy E(keV)</i>	<i>activity (kg-s)⁻¹</i>	<i>energy E(keV)</i>	<i>activity (kg-s)⁻¹</i>	<i>energy E(keV)</i>	<i>activity (kg-s)⁻¹</i>	<i>energy E(keV)</i>	<i>activity (kg-s)⁻¹</i>
<i>Strongest Gammas > 110 keV</i>	238.59	3.61x10⁰⁸	117.16	9.99x10 ⁰²	454.97	5.99x10⁰²	143.79	7.84x10⁰⁶	112.75	9.10x10⁰²	258.18	3.88x10 ⁰²
	277.28	5.63x10 ⁰⁷	118.97	1.14x10 ⁰³	508.2	3.39x10 ⁰²	163.38	3.51x10 ⁰⁶			742.82	3.87x10 ⁰²
	510.61	1.79x10⁰⁸	120.81	7.49x10 ⁰²	581.78	2.77x10 ⁰²	185.74	3.96x10⁰⁷			766.41	1.42x10⁰³
	583.02	7.12x10⁰⁸	135.33	7.85x10 ⁰²			202.14	7.47x10 ⁰⁵			786.29	2.34x10 ⁰²
	727.25	5.51x10 ⁰⁷	145.29	5.71x10 ⁰²			205.33	3.51x10 ⁰⁶			1001	4.45x10⁰³
	860.3	9.93x10 ⁰⁷	146.35	2.25x10⁰³			221.4	8.96x10 ⁰⁴			1193.74	6.16x10 ⁰¹
	2614.35	8.26x10⁰⁸	164.51	2.35x10⁰³			279.5	2.02x10 ⁰⁵			1510.11	6.23x10 ⁰¹
			187.94	7.14x10 ⁰²							1737.8	9.72x10 ⁰¹
			208.15	8.92x10 ⁰²							1831.7	7.67x10 ⁰¹
			217.13	1.25x10 ⁰³								
			245.29	1.25x10 ⁰³								
			291.32	1.86x10 ⁰³								
			317.13	3.14x10⁰³								
			320.51	1.11x10 ⁰³								

^a ²³²U in equilibrium with ²²⁸Th (1.9 years half-life) and subsequent short-lived decay products.

^b ²³⁸U in equilibrium with ^{234m}Pa (1.17 minutes half-life)

^c representative compositions for WGU, actual compositions will vary

Reference: [Browne, 1986]

In the design study referred to above, a weapon made with ^{235}U enriched from natural uranium (thus containing no ^{232}U) with a DU tamper would emit about 10^5 1001 keV gamma rays per second from ^{238}U . If a tungsten tamper were used, the emission would be only about 50 gamma rays per second [Fetter, 1990], which would be virtually undetectable above background. This is clearly a worst-case scenario for detection and not at all typical. A crude weapon constructed by a terrorist organization is likely to contain considerably larger amounts of fissile material, thus making it more readily detectable.

Table 4 lists the primary gamma-ray activities greater than 110 keV for each component of WGPu, with the most prominent gamma rays bolded. ^{241}Am builds up due to decay of ^{241}Pu , which has a relatively short half-life of 14.4 years. The table shows the ^{241}Am activities after 3 years of ingrowth from ^{241}Pu . The strength of the gamma-ray emissions from this isotope is useful as an indicator of the age of the plutonium. ^{241}Am also emits a very intense 59 keV gamma ray, which may be detectable in lightly shielded material.

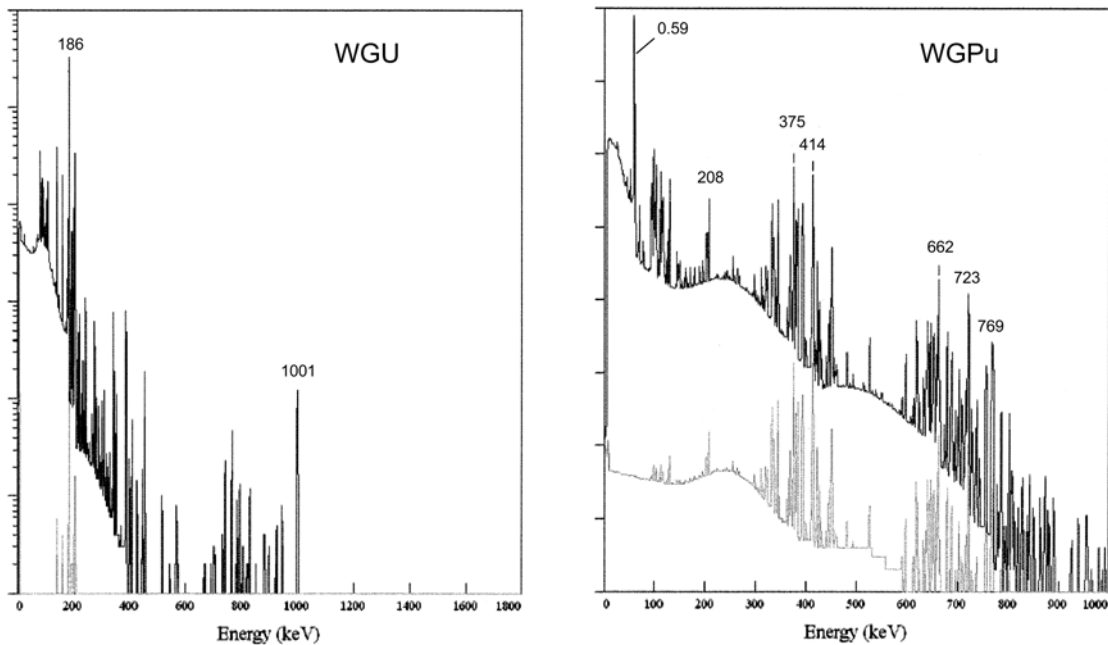


Figure 5. Computer simulations of high-resolution gamma-ray spectra of WGU (left) and WGPu (right). The most prominent peaks are labeled with their energies in keV. The top spectrum includes self-attenuation only. The bottom spectrum is the result of typical additional attenuation for a source inside a “generic” cargo container. Not included are the effects of the environmental background, which would obscure all but the strongest peaks. The WGPu peak labeled 0.59 is from the decay of ^{241}Am . [Geelhood, 2002].

Figure 5 shows computer simulations of high-resolution gamma-ray spectra from WGU and WGPu. The 186 and 1001 keV peaks are prominent in the WGU spectrum. There is a complex series of peaks in WGPu from ^{239}Pu with energies in the range 300 to 500 keV. The strongest of these at 375 and 414 keV are a characteristic signature for WGPu. For each material, the top spectrum is for a bare source and the bottom spectrum is attenuated by 1 cm of iron and 50 cm of polyethylene to represent the spectrum observed outside a typical cargo container. In a real measurement, these spectra would be superimposed over the background due to environmental radiation (see Section 6).

Table 4. Gamma-Ray Activities per Kilogram of Weapons Grade Plutonium

(the most prominent gamma rays are bolded)

<i>mass number</i>	238		239		240		241		241(Am)^a		242	
<i>half-life (years)</i>	87.7		2.41x10 ⁰⁴		2.56x10 ⁰³		14.4		432.7		3.76x10 ⁰⁵	
<i>activity (Bq/kg)</i>	6.34x10 ¹⁴		2.30x10 ¹²		2.15x10 ⁰⁶		3.81x10 ¹⁵		5.91x10 ¹⁴		1.47x10 ¹¹	
<i>WGU Composition</i>	0.005%		93.3%		6.0%		0.40%		0.062% [*]		0.015%	
	<i>energy</i>	<i>activity</i>	<i>energy</i>	<i>activity</i>	<i>energy</i>	<i>activity</i>	<i>energy</i>	<i>activity</i>	<i>energy</i>	<i>activity</i> [*]	<i>energy</i>	<i>activity</i>
	(keV)	(kg-s) ⁻¹	(keV)	(kg-s) ⁻¹	(keV)	(kg-s) ⁻¹	(keV)	(kg-s) ⁻¹	(keV)	(kg-s) ⁻¹	(keV)	(kg-s) ⁻¹
<i>Strongest Gammas > 110 keV</i>	152.69	3.20x10 ⁰⁵	129.28	1.33x10 ⁰⁸	160.31	5.43x10⁰⁶	148.54	2.78x10⁰⁷	146.55	2.34x10 ⁰⁶	158.8	9.89x10⁰¹
	742.82	2.47x10 ⁰³	332.81	1.08x10 ⁰⁷	212.46	3.88x10 ⁰⁵	159.93	1.01x10 ⁰⁶	208.01	4.01x10⁰⁶		
	766.41	1.05x10⁰⁴	344.94	1.22x10 ⁰⁷	642.35	1.29x10 ⁰⁵			322.54	7.72x10 ⁰⁵		
	786.29	1.49x10 ⁰³	375.02	3.39x10⁰⁷	687.59	3.49x10 ⁰⁴			368.59	1.17x10 ⁰⁶		
	808.25	5.45x10 ⁰²	380.17	6.58x10 ⁰⁶					376.58	7.01x10 ⁰⁵		
	851.72	6.43x10 ⁰²	382.68	5.57x10 ⁰⁶					662.43	1.83x10⁰⁶		
	883.24	3.52x10 ⁰²	392.50	2.49x10 ⁰⁶					722.7	6.60x10 ⁰⁵		
	1001	4.34x10⁰²	393.12	9.51x10 ⁰⁶								
			413.83	3.24x10⁰⁷								
			451.44	4.11x10 ⁰⁶								
			645.98	3.11x10 ⁰⁵								
			769.37	2.36x10 ⁰⁵								

^a ²⁴¹Am activity and composition given after 3 years ingrowth from ²⁴¹Pu

Reference: [Browne, 1986]

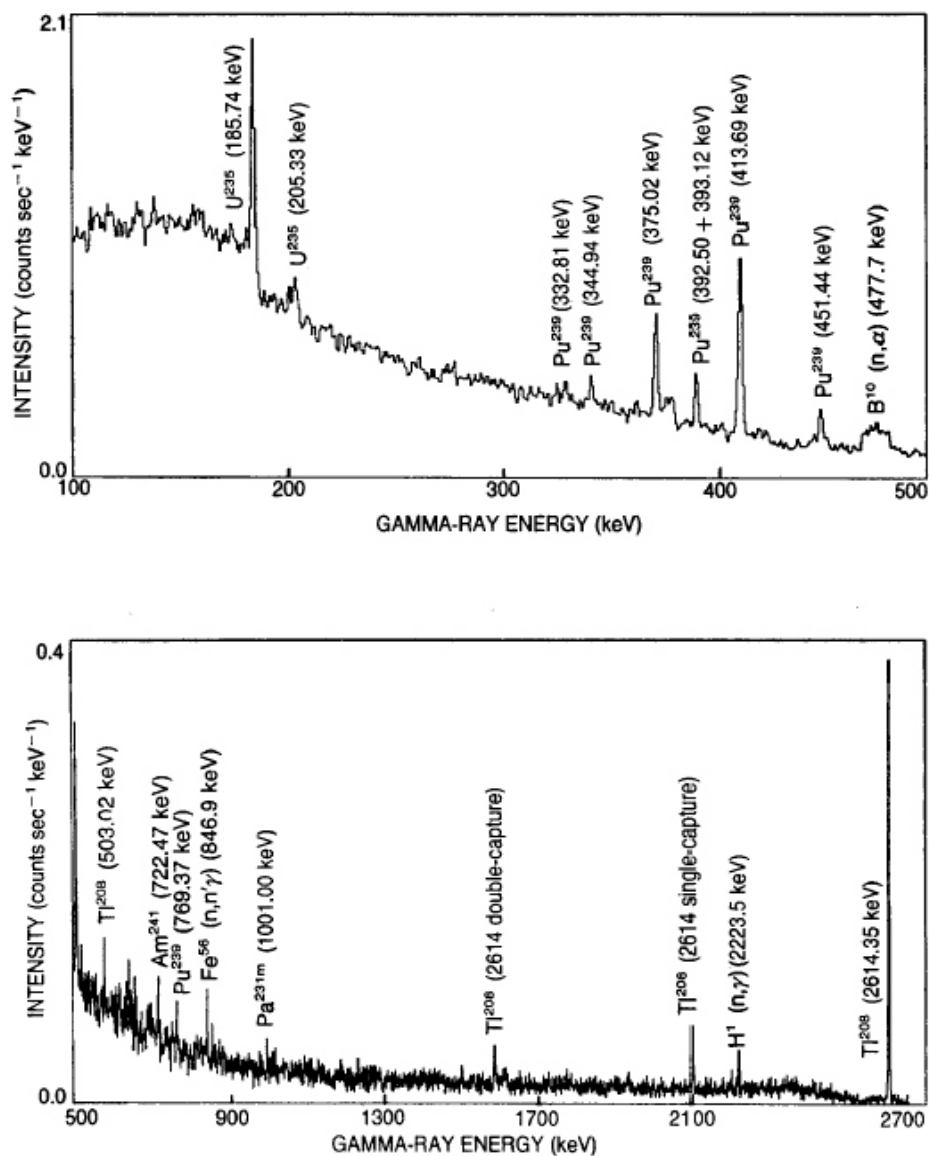


Figure 6. Spectrum taken with a germanium gamma-ray detector, purportedly of a Soviet cruise missile in its launcher. The spectrum was taken for 10 minutes with the detector directly on top of the launcher. [Fetter, 1990A].

Figure 6 shows a high-resolution gamma-ray spectrum purportedly of a Soviet nuclear cruise missile in its launcher, taken by a group of U.S. researchers on a Soviet cruiser in the Black Sea [Fetter, 1990A]. The experimenters were surprised by the “unexpectedly low” 1001 MeV gamma ray from ²³⁸U, indicating very highly enriched uranium with “only about 4% ²³⁸U”, and by the prominent low-energy ²³⁵U gamma rays, indicating “that there is almost no heavy-metal shielding between the ²³⁵U and the detector.” There is a strong possibility that this was a mockup rather than an actual weapon, but it does give some indication of what could be observed under fairly ideal conditions. The large peak at 2614 keV labeled ²⁰⁸Tl, a decay product of ²³²U, indicates that the HEU comes from reprocessed uranium.

A hypothetical WGPu weapon with a heavy tungsten tamper would strongly attenuate the gamma rays below 600 keV [Fetter, 1990 (Appendix B)]. In this case the strongest gamma-ray emissions would likely be the 662 and 722 keV gamma rays from ^{241}Am and the 646 and 769 keV gamma rays from ^{239}Pu . Even if these gamma rays were heavily shielded, a weapon constructed from WGPu would likely still be detectable via its strong neutron emissions, which are difficult to shield.

An on-line catalog of gamma-ray spectra taken with Ge and NaI detectors for sources of individual radionuclides is available at [INEEL, 2004]. Included are tables of gamma-ray decay energies and intensities. Links are also given to other compilations of nuclear data.

C. Radiological Weapons

It is unlikely, but within the realm of possibility, that a terrorist group or rogue state would be able to acquire and deliver a nuclear weapon. There are many obstacles to overcome, including a) circumventing security measures at nuclear facilities and storage sites to acquire a weapon or sufficient material to build one, b) smuggling the weapon or material to a safe site, c) engineering and building a weapon or unlocking the safeguards on a stolen weapon, d) smuggling the weapon into the country to be attacked and e) successfully detonating the weapon [Washington Post, 2004].

Much more likely is an attack using a radiological weapon or “dirty bomb.” Such a weapon would combine a chemical explosive with radioactive material diverted from a medical or industrial facility or with highly radioactive spent reactor fuel. The blast effects would be confined to nearby buildings. However, the radioactive material could be dispersed over an area of a few city blocks to many square miles, depending on the characteristics of the explosion, the type of radioactive material, and weather conditions. Any immediate deaths would be due to the effects of the blast. In most cases, the population exposed to the radioactive material could be evacuated before receiving a lethal dose. The primary damages of such an attack would be the psychological effects on the population and the economic costs due to loss of use of the buildings in the contaminated area, plus the costs of cleanup. A recent study concludes that if the winds were right, an explosion at the tip of Manhattan (figure 7) using a stolen industrial cobalt source could cause long-term contamination of an area up to the middle of Central Park [FAS, 2002].



Figure 7. Simulation of a dirty bomb using an industrial cobalt source normally used for food irradiation. The inner contour shows contamination at radiation levels equal to the permanent exclusion zone at Chernobyl. The middle contour equals the permanently controlled zone and the outer contour the periodically controlled zone. [FAS, 2002].

The use of spent reactor fuel in a radiological attack could have far-ranging effects. The U.S. spent nuclear fuel inventory has an average activity of about 150 Ci/kg (5×10^{12} Bq/kg)^a [EPA, 2003]. A computer model indicates that fallout from a weapon using spent nuclear fuel could deliver a lethal dose in a 24-hour period over a broad area extending as far as 400 km [Nichelson, 1999]. Figure 8 shows a simulation using historical wind patterns on March 2, 1999. A shift in the winds could have delivered a 24-hour lethal dose to Washington, DC, and spread serious contamination as far as Philadelphia and New York City. However, the difficulties in making, handling, and delivering such a weapon without receiving a lethal or debilitating dose could limit its use, while the radioactivity from such a device would be easily detectable and difficult to shield during transport.

^a The SI unit for radioactivity is the becquerel (Bq), named after the discoverer of radioactivity, and defined as one disintegration per second. The traditional unit is the curie (Ci) defined as 3.7×10^{10} Bq. Both are in common use since the Bq is inconveniently small in many contexts, while the Ci is often inconveniently large.

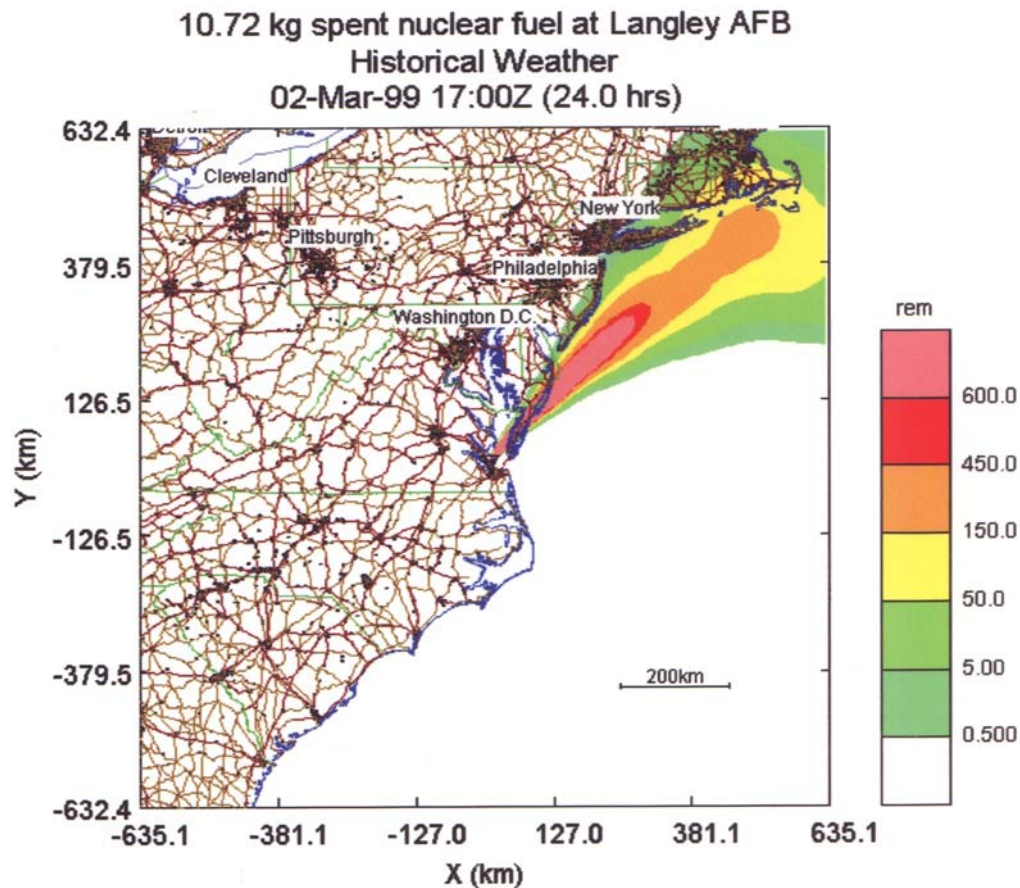


Figure 8. Simulation of a radiological attack at Langley AFB, Virginia, using 10.27 kg of spent nuclear fuel. Cumulative dose contours after 24 hours are given in rem, which is the biological equivalent dose. A dose of 600 rem (6 Sv) or greater during a 24-hour period is usually fatal [Nichelson, 1999].

In addition to explosive devices, a recent comprehensive study also considered non-explosive dispersion scenarios, which have the potential of exposing a large population to lethal amounts of radiation before local authorities become aware of the danger and begin evacuations [Zimmerman, 2004]. The worst-case scenario assumes that terrorists devise an efficient means of aerosol dispersion of a stolen Russian mobile seed irradiator containing up to 250,000 Ci of ^{137}Cs . If this device were set off in a large city, the death toll could reach hundreds or thousands, with economic costs in the billions of dollars. Most of these deaths could be averted by installation of radioactivity monitors, allowing prompt evacuation in the case of such an attack.

D. Radiological Sources

The primary potential sources of material for radiological weapons are medical, industrial and research sources, and spent nuclear fuel. The most hazardous of these from a radiation safety perspective are ranked in category 1 by the IAEA [Ferguson, 2003]. These are listed in table 5

along with their typical activity levels. Table 6 lists for these sources the half-lives and types of radiation emitted and their energies. By their nature, the sources used for irradiation all produce energetic and penetrating gamma rays. They are hard to shield and difficult to transport safely. ^{90}Sr , used for radioisotope thermal power generators, emits only low-energy betas that are easily shielded. However, its short-lived decay product, ^{90}Y , emits a high-energy beta that, when stopped in the shielding material, produces a continuous bremsstrahlung^a photon spectrum peaked below 200 keV [McCain, 2002; Brodzinski, 1980].

Table 5. Medical, Industrial, and Research Radiation Sources

<i>Application</i>	<i>Radioisotope</i>	<i>Activity Level (Ci)</i>
Radioisotope Thermal Generators	^{90}Sr	30,000 -- 300,000
Radiotherapy	^{60}Co	1,350 -- 27,000
	^{137}Cs	13,500
Blood irradiation	^{137}Cs	50 -- 2700
Industrial irradiation	^{192}Ir	3 -- 250
Sterilization and Food Irradiation	^{60}Co	2,700 -- 11×10^6
	^{137}Cs	2,700 -- 11×10^6
Research Irradiators	^{60}Co	27 -- 27,000
	^{137}Cs	27 -- 27,000

Reference: [Ferguson, 2003]

Table 6. Medical, Industrial, and Research Source Characteristics

<i>Isotope</i>	<i>half-life</i>	<i>type of radiation</i>	<i>energy (keV)</i>
^{90}Sr	28.8 years	beta	546*
$\rightarrow ^{90}\text{Y}$	2.67 days	beta	2228*
		bremsstrahlung	continuous
^{137}Cs	30.1 years	beta	1175*
		gamma	662
^{192}Ir	74 days	beta	669*
		gamma	296, 308, 316, 468
^{60}Co	5.3 years	beta	669*
		gamma	1173, 1332

* endpoint energy

Reference: [Browne, 1986]

Spent nuclear fuel is a strong source of alphas, betas, gamma rays and neutrons. Table 7 gives the activities of the primary isotopes in the U.S. spent nuclear fuel inventory [EPA, 2003]. As discussed earlier, its high radiation level makes spent nuclear fuel a difficult material for construction of a radiological weapon, but one that could have dire consequences if dispersed in an explosion.

^a The word bremsstrahlung comes from German and literally means braking radiation.

Table 7. U.S. Radionuclide Inventory

Isotope	Half-life (years)	Activities (> 100 Ci per metric ton)			Weighted Average
		Commercial	DOE/DOD		
		BWR ^a	PWR ^b	HLW ^c	
¹³⁷ Cs	30.2	51,800	69,600	29,700	60,000
⁹⁰ Sr	28.8	37,900	49,100	29,300	43,600
²⁴¹ Pu	14.4	30,900	46,100	349	36,700
²⁴¹ Am	433	2,500	3,670	1,050	3,040
²³⁸ Pu	87.7	1,610	2,870	977	2,280
²⁴⁴ Cm	18.1	3,520	9,860	27.70	689
²⁴⁰ Pu	6,570	464	53,400	7.77	459
⁶³ Ni	100	132	544	8.13	357
¹⁵¹ Sm	90	280	366	466	349
²³⁹ Pu	24,100	297	353	11.30	301

^a BWR: boiling water reactor (units of Ci per initial metric ton of heavy metal)

^b PWR: pressurized water reactor (units of Ci per initial metric ton of heavy metal)

^c HLW: high level waste (units of Ci per metric ton of heavy metal)

Reference [EPA, 2000]

Neutron sources such as ²⁵²Cf or ²⁴¹Am/Be are also used for industrial and research applications. These usually have higher average neutron energy than WGPu, but they may be moderated in energy by neutron scattering materials such as polyethylene. These sources are also strong gamma-ray emitters. ²⁵²Cf has a continuous high-energy gamma-ray spectrum with no distinct peaks. ²⁴¹Am/Be makes use of capture by beryllium of high-energy alpha particles from ²⁴¹Am, followed by neutron emission. This reaction also emits high-energy 4.43 MeV gamma rays in addition to low-energy 59 keV gammas from ²⁴¹Am.

5. Background Radiation

A. Gamma-Ray Background

The natural gamma-ray background is a combination of terrestrial, atmospheric and cosmic ray induced gamma rays. A typical gamma-ray background spectrum is shown in figure 9 with the most prominent background peaks marked.

The terrestrial background is constant at a given location unless there is a substantial change in nearby structures. This background has three main components from the decay of ²³²Th, ²³⁸U, and ⁴⁰K, generally referred to as thorium, uranium, and potassium. Thorium and uranium have long decay chains through short-lived “daughter” nuclei, primarily by alpha or beta particle emissions, which are not detectable. However, some of the intermediate decay products are also strong gamma-ray emitters. Table 8 gives the gamma rays from the decay chains of the “parent” background components, assuming equilibrium with their decay products. The most prominent gamma rays from each component are bolded. The branching fraction is the equilibrium gamma-ray intensity per decay of each parent nuclide.

- Thorium activity is due to decay products from ^{232}Th , which has a half-life of 1.4×10^{10} years and is found in most rocks, soils, and building materials, such as concrete and brick. It decays through a series of short-lived isotopes ending in stable ^{208}Pb . The most prominent gamma rays are 239 keV from ^{212}Pb , 511, 583 and 2614 keV from ^{208}Tl , and 911 and 969 keV from ^{228}Ac . The ^{232}Th and ^{232}U decay chains are similar, with the exception that ^{228}Ac occurs only from ^{232}Th decay. Thus, the observation of the ^{228}Ac gamma rays serves to distinguish the spectrum of ^{232}Th from that of ^{232}U .
- Uranium activity is due to decay products from ^{238}U , which has a half-life of 4.5×10^9 years and, like thorium, is found in most rocks, soils and, building materials. It decays through a series of shorter-lived isotopes ending in ^{206}Pb . The most prominent gamma rays are 609, 1120, and 1764 keV from ^{214}Bi .
- Potassium activity is due to decay of ^{40}K , which has a half-life of 1.28×10^9 years. It has a single very prominent 1461 keV gamma ray.

The open-ocean background is similar to the terrestrial background but has about one-tenth the strength of the background over land. Over fresh water and over the ocean near the shore, the background intensity depends on how much sediment is suspended in the water.

The atmospheric background can vary considerably with wind direction and meteorological conditions. This activity is mostly due to short-lived decay products from ^{222}Rn gas (3.8 day half-life), which is emitted from decay of soil deposits of ^{226}Ra (1600-year half-life), a member of the ^{238}U decay chain. Radon gas often builds up in the soil and can then be released in a burst, which may travel tens of kilometers with the wind as a “radon cloud”. The prominent gamma rays in figure 9 at 609, 1120, and 1764 keV are emitted by the radon decay product ^{214}Bi .

The cosmic-ray background is characterized by a 511 keV gamma ray induced by cosmic-ray interactions. This comes about when high-energy cosmic rays (mostly muons at sea level with average energies of 100 MeV or greater) interact with matter, producing primarily neutrons and pairs of fast-moving positive and negative electrons. The positive electron or “positron” is the antiparticle of the ordinary negative electron. It eventually slows down enough to be attracted by and annihilate with a negative electron, producing two 511 keV gamma rays. The intensity of the cosmic-ray background increases rapidly above sea level and dominates the gamma-ray background spectrum at cruising altitudes of aircraft.

Underlying the gamma-ray peaks in figure 9 is a strong, continuous background spectrum, which is highest at low energies. This is due primarily to higher-energy gamma rays that are only partially absorbed by the detector. At higher altitudes there is also a strong contribution to the background continuum from high-energy cosmic rays, which produce a continuous bremsstrahlung spectrum as they slow down in the material in the vicinity of the detector.

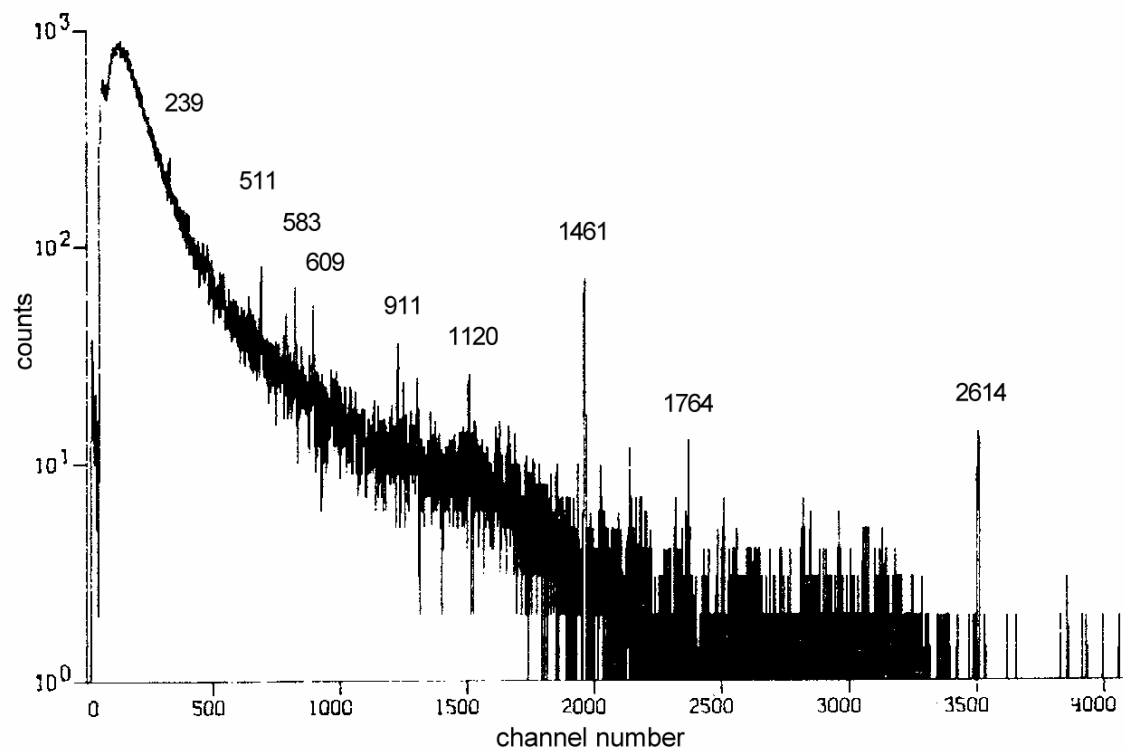


Figure 9. A typical high-resolution gamma-ray background spectrum, taken for 4096 seconds with a 15% relative efficiency detector. The most prominent peaks are labeled with their energies in keV. The scatter in the spectrum is due to random statistical variations.

Table 8. Terrestrial Background Gamma Rays

(the most prominent gamma rays are bolded)

<i>background nuclide</i>	²³² Th			²³⁸ U			⁴⁰ K		
<i>half-life (years)</i>	1.41x10 ¹⁰			4.47x10 ⁰⁹			1.28x10 ⁰⁹		
<i>activity (Bq/kg)</i>	4.06x10 ⁰⁶			1.24x10 ⁰⁷			2.59x10 ⁰⁸		
	<i>energy (keV)</i>	<i>branching fraction</i>	<i>decay product</i>	<i>energy (keV)</i>	<i>branching fraction</i>	<i>decay product</i>	<i>energy (keV)</i>	<i>branching fraction</i>	<i>decay product</i>
<i>strongest</i>	238.58	43.60%	²¹² Pb	241.92	7.46%	²¹⁴ Pb	1460.83	10.67%	⁴⁰ K
<i>gammas</i>	240.76	3.90%	²²⁴ Ra	351.87	37.10%	²¹⁴ Pb			
<i>> 110 keV</i>	277.28	6.80%	²⁰⁸ Tl	609.31	46.10%	²¹⁴ Bi			
	300.03	3.34%	²¹² Pb	665.44	1.56%	²¹⁴ Bi			
	338.42	12.40%	²²⁸ Ac	768.35	4.88%	²¹⁴ Bi			
	463.1	4.60%	²²⁸ Ac	785.83	1.09%	²¹⁴ Pb			
	510.61	21.60%	²⁰⁸ Tl	806.16	1.23%	²¹⁴ Bi			
	583.02	86.00%	²⁰⁸ Tl	934.04	3.16%	²¹⁴ Bi			
	727.25	6.65%	²¹² Bi	1120.27	15.00%	²¹⁴ Bi			
	763.06	1.64%	²⁰⁸ Tl	1555.18	1.69%	²¹⁴ Bi			
	794.79	4.60%	²²⁸ Ac	1238.11	5.92%	²¹⁴ Bi			
	860.3	12.00%	²⁰⁸ Tl	1280.95	1.47%	²¹⁴ Bi			
	911.16	29.00%	²²⁸ Ac	1377.66	4.02%	²¹⁴ Bi			
	964.64	5.80%	²²⁸ Ac	1401.48	1.39%	²¹⁴ Bi			
	968.97	17.40%	²²⁸ Ac	1407.97	2.48%	²¹⁴ Bi			
	1496	1.05%	²²⁸ Ac	1509.22	2.19%	²¹⁴ Bi			
	1588.23	3.60%	²²⁸ Ac	1661.26	1.15%	²¹⁴ Bi			
	1620.66	1.51%	²¹² Bi	1729.58	3.05%	²¹⁴ Bi			
	2614.35	99.79%	²⁰⁸ Tl	1764.49	15.90%	²¹⁴ Bi			
				2118.53	1.21%	²¹⁴ Bi			
				2204.09	4.99%	²¹⁴ Bi			
				2447.68	1.55%	²¹⁴ Bi			

Reference: [Browne, 1986]

B. Neutron Background

The natural neutron background is mostly due to cosmic-ray interactions with the atmosphere, the ground, and massive objects such as buildings, ship superstructures and cargo (a phenomenon known as the “ship effect,” because it was first observed in the neutron signal from large ships.) It peaks in energy at about 1 MeV and drops off rapidly above this. At sea level, the average cosmic-ray neutron production is about 20 neutrons per kg of material per second. This results in a neutron flux of 100-300 neutrons/m²/s. The average neutron background varies with geomagnetic latitude and is highest above 45 degrees, dropping to a low point at the equator. It also varies with solar activity and is approximately a factor of two higher during the solar minimum, when the shielding effect of the sun’s magnetic field is lowest. During solar flares, the neutron background at high latitudes increases dramatically due to atmospheric interactions with energetic charged particles emitted by the flare. This variability must be considered when using a neutron detector. In addition, an inspector must know the expected amplitude of the ship effect, or cosmic-ray induced neutron signature, from any massive cargo container, to avoid mistaking it for a suspect source.

C. Man-Made Background

Since the cessation of atmospheric nuclear testing, man-made background due to fallout has declined to levels well below the natural background. Except in regions contaminated by nuclear accidents, such as Chernobyl, or by an occasional lost medical or industrial source, man-made background will not be an appreciable contribution to the radiation background.

D. Detection Capabilities in the Natural Radiation Environment

Several factors come into play in determining whether a nuclear weapon or nuclear material is detectable above the natural radiation background. These include the configuration of the weapon or material, the amount of shielding, the type of detector, the level of the radiation background, the distance from the source, and the counting time. In general, the instrumental noise in the detector is negligible compared to the random statistical noise due to variations in the counts due to the background and the source.

Figure 10 shows the calculated gamma-ray counts versus distance for the signal from a hypothetical WGU nuclear weapon [Fetter, 1990] with a thick, depleted uranium tamper, which emits 100,000 gamma rays per second with energy 1001 keV. The calculation assumes the use of a large 100% relative efficiency Ge detector with detection efficiency at 1001 keV of 1.35×10^{-4} for a point source one meter from the detector. It takes into account the geometrical $1/R^2$ decrease with range R for the signal from a point source, as well as the air attenuation of the gamma rays. The solid line shows the calculated counts per 1000 seconds versus distance for the 1001 keV gamma-ray peak from the WGU source. The dashed line shows the expected counts in the region of the 1001 keV peak for a typical gamma-ray background and the dotted line shows the three standard deviation level “3-sigma” due to random variations in the total (peak plus background) counts^a. A good rule of thumb is that the signal from the weapon is detectable if it is

^a Sigma is the statistical standard deviation in the total counts, which is equal to the square root of the sum of the peak counts plus background counts in the region of the peak.

greater than three times the standard deviation in the signal. Using this rule, the gamma-ray signal is detectable out to a range of about 19.2 meters.

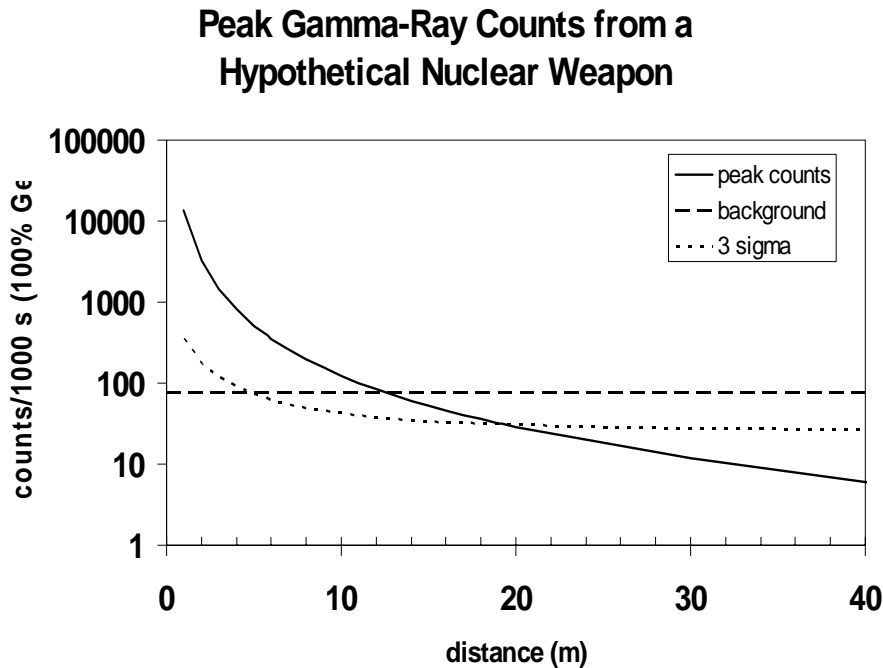


Figure 10. Peak gamma-ray counts (solid curve), background counts (dashed line) and 3-sigma standard deviation level (dotted line) plotted versus distance for a 1000-second observation of a hypothetical WGU weapon using a 100% relative efficiency Ge detector. The signal is detectable as long as the peak counts are above the 3-sigma level.

Figure 11 shows the calculated neutron counts versus distance for the signal from a hypothetical WGPu weapon that emits 400,000 neutrons per second. The calculation assumes the use of a large 1-square-meter-area neutron detector with an absolute efficiency of 10^{-4} per neutron. This gives a detection efficiency of about 8×10^{-6} for a point source one meter from the detector. The solid line shows the calculated counts for 1000 seconds for neutrons from the WGPu source. The dashed line shows the expected counts for a typical background flux of $300 \text{ m}^{-2}\text{s}^{-1}$, and the dotted line shows the 3-sigma level. Using the above rule of thumb, the neutron signal is detectable out to about 11.8 meters.

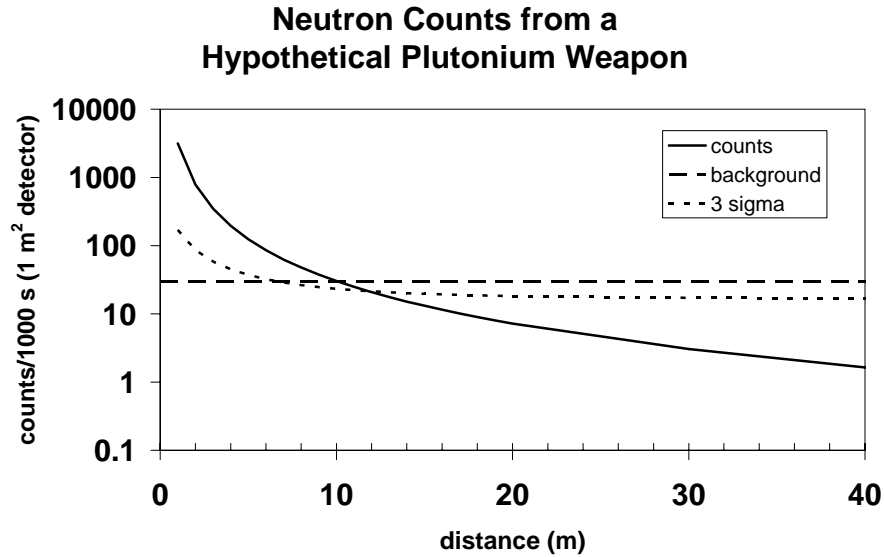


Figure 11. Neutron counts (solid curve), background counts (dashed line), and 3-sigma standard deviation level (dotted line) plotted versus distance for a 1000 second observation of a hypothetical WGPu weapon emitting 400,000 neutrons per second, using a 1 square meter neutron detector. The signal is detectable as long as the counts from the weapon are above the 3-sigma level.

Table 9 shows how the detection range for WGU and WGPu weapons varies with counting time, detector size (or number of detectors), and source strength. A rough approximation is that an N -fold increase in source strength increases the detection range by $N^{1/2}$, while an N -fold increase in counting time or detector size, which raises both the source counts and the background counts, increases the detection range by only $N^{1/4}$. The last row of the table shows the detection range if the WGU gamma-ray source is shielded by 1 cm lead and the WGPu neutron source by 10 cm polyethylene. This reduces the detection range from 19.2 to 13.4 meters for the WGU weapon and from 11.8 to 6.7 meters for the WGPu weapon. For a given source, to double the ratio of the signal to 3-sigma level, one would need to increase the product of the counting time and detector size by a factor of four. If possible, the best detection strategy is to get closer, which increases the signal without increasing the background.

Table 9. Detection ranges for hypothetical nuclear weapons

<i>WGU gamma-ray emitting weapon</i>				<i>WGPu neutron emitting weapon</i>			
<i>number of detectors^a</i>	<i>counting time (s)</i>	<i>gamma-ray source (s⁻¹)</i>	<i>range (m)</i>	<i>detector area (m²)</i>	<i>counting time (s)</i>	<i>neutron source (s⁻¹)</i>	<i>range (m)</i>
one	100	100,000	9.5	1	100	400,000	5.2
one	1000	100,000	19.2	1	1000	400,000	11.8
two	1000	100,000	23.1	2	1000	400,000	14.5
ten	1000	100,000	34.1	10	1000	400,000	22.4
one	1000	1,000,000	53.0	1	1000	4,000,000	35.2
one	1000	46,300 ^b	13.4	1	1000	126,000 ^c	6.7

^a 100% relative efficiency Ge detectors

^b 100,000 s⁻¹ source shielded by 1 cm lead

^c 400,000 s⁻¹ source shielded by 10 cm polyethylene

6. Nuclear Radiation Detection

A. General Aspects of NRWMD Detection

The detection technologies relevant to locating WMD are generally complex in both their design and employment. They almost always involve the tight integration of cross-cutting capabilities from multiple scientific and engineering disciplines. Production of a detection instrument requires exploitation and optimization of one or more generally sophisticated physical, chemical, or biological mechanisms. It also requires expertise in materials and in electrical and mechanical engineering. Many engineering tradeoffs are needed for designing such systems to achieve adequate performance and reliability at reasonable costs. An instrument that offers such performance at acceptable costs is inevitably a tight integration of electrical and mechanical components. Instruments intended for use in the field require attention to thermal, vibrational, and other environmental factors. Design and performance trade-offs are virtually unavoidable. Care needs to be taken that the complexity of design and fabrication does not translate into a complexity of operation. Attention to the user interface and training is important to minimize operator error. Provision of needed supplies and spare parts is a logistical requirement. Successful utilization of any of the detection technologies for NRWMD hinges on proper care for the instrument, including routine maintenance and re-calibration.

There are two fundamental classes of means for detecting and assaying the materials that may be made into or already constitute an NRWMD. The first class is technologies to find and exploit some signature that indicates the presence of nuclear or radiological material. Typically these technologies exploit spontaneous radioactive emissions from nuclear materials or emissions stimulated by x-rays, gamma rays, or neutrons. The second class of detection technologies involves finding NRWMD devices. They often involve the acquisition of images that reveal these devices from their shape or from surrounding materials. Very large radiography systems, using either high-energy x-rays or gamma rays, can image the contents of an entire truck or container.

Whatever the WMD materials of interest, there are some fundamental and general aspects of the instruments that will detect, identify, and quantify these substances. In the most general

terms, a detection technology is embodied in an instrument that accepts signals or samples molecules from nuclear materials and turns them into information. This is indicated schematically in figure 12.

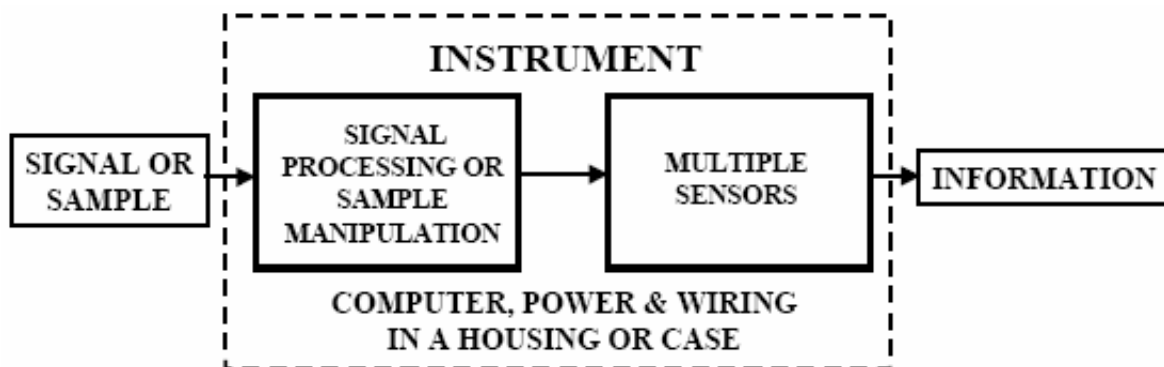


Figure 12. Diagram of the most basic components of a detection technology

The front end of a detection device may include filters or masks for nuclear radiation. Ultimately, the external energy is sensed by one or more sensors that transform the input into data. The computer, which is commonly built into an instrument, turns the data into information for display, storage, processing, or transmission. The system must provide power, communication of the components, and be contained in a protective housing or case.

The detection of nuclear materials by their natural or stimulated radiation requires the employment of a detector system with a few subsystems based on physical interactions. The general layout of such systems is shown in figure 13.

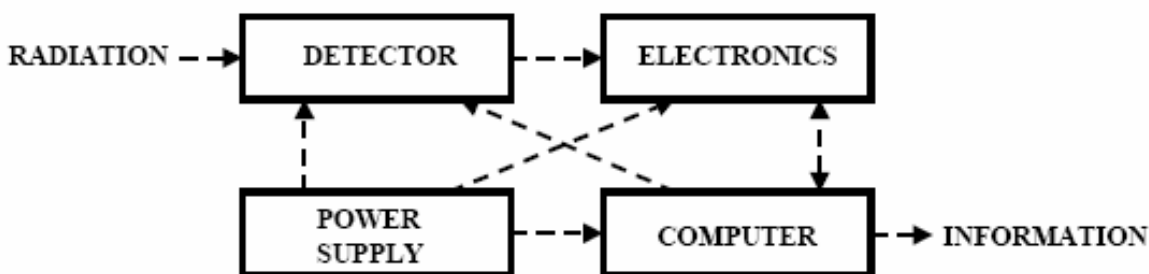


Figure 13. General layout of systems for detection of nuclear radiations

The key element is the detector itself, which consists of materials of sufficient size and proper geometry to absorb energy from incident radiation and convert that energy into some other measurable form. In general, an electrical signal results, which is usually processed by electronics, such as pulse amplifiers and counters that register the number of arriving pulses with defined characteristics. Some detector systems are insensitive to the energy of the incident radiation. If so, it may be possible to determine the radiation energy range by absorbers between the source and detector, or by using detectors of varying thicknesses.

The problem of detection of an NRWMD usually involves low count rates and the use of detector systems that yield pulses that vary in size with the energy of the incident radiation. In this case, a spectrum results from the display of the number of counts for each incident energy increment. Examples of such spectra are shown in figures 6 and 9. Whatever the detector behavior, the resulting digitized information is stored in the computer. This information is available for display, further manipulation, or transmission. Special-purpose software is required to perform both the control functions and the data handling. A common function is to apply corrections to the data to account for energy-dependent responses of the materials and the detector. After making these corrections, the energies and intensities of gamma-ray peaks observed in the spectra can be compared with stored values for materials of interest.

Nuclear detection instruments share a set of characteristics with detection technologies for all WMD. The use of calibration curves, which relate count rates to the amount of material, is one of them. The threshold behavior near the limit of detection for weak nearby radiation sources, or strong sources at a greater distance, is another. Threshold detection is very dependent on the environmental and operating conditions, as well as the radiation source and the detection instrument. Calibration and operating curves are discussed in Appendix A. There are also practical considerations that apply to the choice of detection technologies for nuclear materials and other WMD. These are reviewed in Appendix B.

B. Characteristics of Radiation Detectors

The observable gamma rays and neutrons from nuclear weapons or materials have mean free paths of the order of hundreds of meters in air and one to ten centimeters in water and solids, as given in table 1. This physical fact means that useful detectors cannot be too small or lightweight. Typical detectors have volumes of tens or hundreds of cubic centimeters and weigh several kilograms. Lightweight, portable detectors exist, but they can only be used for relatively strong sources at close range. A general discussion of the detection process is given here. This is followed by more detailed descriptions of individual detector types. A useful source of information on radiation detectors can be found in [Knoll, 2000].

Gamma rays and neutrons are both long-range neutral particles that do not produce an electrical signal when they pass through the detector. For detection, their energy must be transferred to short-range charged particles. Gamma rays interact with the detector to produce energetic electrons. These lose energy in semiconductor detectors by producing particle-hole pairs, which are swept up by an applied voltage to give an electrical signal. Similarly, in gas-filled detectors, such as proportional counters and Geiger counters, the energetic electrons ionize the gas, producing electron-ion pairs, which are then swept up by an applied voltage. In scintillation detectors, the electrons interact to excite the crystal structure, which then decays by emitting photons. These are converted to an electrical signal by the use of photomultiplier tubes or photodiodes.

Radiation exposure monitors, such as x-ray film or personnel dosimeters, record a physical change in the material caused by the radiation. When the film is developed or the dosimeter read out, a record of the cumulative radiation exposure is obtained. Radiation detectors convert the radiation in real time to an observable effect, such as electronic pulses or scintillator light. The Geiger counter is the simplest type of detector, using a voltage applied across a gas-filled tube to convert radiation into electric pulses that can produce an audible click. The survey meter is a similar device, which is usually calibrated to give a meter reading in units of dose rate. More

sophisticated detectors give additional information, such as the radiation energy, which can be used to identify the source.

Gamma-ray detectors are available as hand-held scintillation crystals, such as thallium activated sodium iodide (abbreviated NaI(Tl) or often just NaI), which convert gamma radiation to light. The light is further converted by a photomultiplier to an electronic signal, whose pulse-height is proportional to the gamma-ray energy. These signals are recorded by a pulse-height analyzer (PHA), which displays a spectrum of counts versus gamma-ray energy. NaI detectors have a limited energy resolution of about 8% for the 662 keV gamma rays from ^{137}Cs .

Solid-state semiconductor detectors convert the gamma-ray energy directly to an electronic pulse that is then recorded by a PHA. Germanium (Ge) detectors have an energy resolution of about 0.2%, or forty times better than NaI, and produce a high-resolution spectrum with sharp peaks rising above an underlying continuum. This superior resolution allows precise determination of the gamma-ray energy, separation of close-lying peaks, and identification of weak peaks in the presence of a strong interfering background. The disadvantage of Ge detectors is that they require cooling to below 100 degrees Kelvin, either by liquid nitrogen or electro-mechanical coolers. This makes the detector system heavier than NaI and adds logistical problems in the field, requiring a source of liquid nitrogen or additional power to drive the cooler. For this reason, much effort has gone into developing room-temperature semiconductor detectors, such as cadmium zinc telluride (CZT) or mercuric iodide (HgI). These have resolutions down to about 2%, superior to NaI but no match for Ge detectors. To date they have not been produced in volumes of more than a few cm^3 compared to several hundred cm^3 for Ge and several thousand cm^3 for NaI. Their small volumes limit not only the sensitivity of room-temperature semiconductor detectors but also their ability to stop high-energy gamma rays. Thus, Ge detectors remain the best choice for detecting and identifying gamma rays from nuclear materials.

Both in semiconductor and scintillation detectors, the electrical signal is proportional to the energy deposited in the detector. By the use of specialized nuclear electronics, this signal is amplified and shaped into a short pulse whose height is proportional to the original signal strength. Pulse height converters digitize the signal, which is then sent to a computer and used to construct an energy spectrum that can be displayed on a monitor. Gamma-ray detector electronics are described in greater detail in Section 7.

All neutron detectors work by detecting the charged particles produced when the neutrons interact with a suitable material. Neutron absorption is most efficient for low-energy thermal neutrons, so these detectors include a moderating material, which slows the neutron down by elastic scattering. After absorption, the excited nucleus decays, emitting a charged particle, which can be detected by a scintillator, semiconductor diode or gas-filled counter. The neutron energy information is lost in the moderation process, so the resulting display is typically count rate or is converted to dose rate. The most common neutron detectors are proportional counters containing a gas, such as ^3He or BF_3 , that has high thermal neutron capture probabilities. Solid-state neutron detectors are in development, which contain a thermal neutron capture material, such as ^{10}B or ^6Li , followed by a semiconductor particle detector. All of these detectors require a moderator to slow the fission energy neutrons emitted by nuclear materials. Fast neutron detectors, which do not contain a moderator, have several orders of magnitude lower sensitivity.

C. Employment Scenarios

The best detection equipment will not be effective unless it is in the right place at the right time and in the hands of trained inspectors. In an exercise reported by ABC News [Ross, 2002] a mock-up of a nuclear weapon, consisting of 15 lbs of depleted uranium shielded by a steel pipe



Figure 14. Nuclear weapon mock-up in a suitcase [Ross, 2002].

with a lead lining inside a suitcase (figure 14), was transported by rail from Austria to Turkey, passing through multiple border checkpoints without being inspected. An x-ray or gamma-ray scan of this mockup would have surely indicated something suspicious. It was then crated and shipped by sea from Istanbul to New York. There it passed through U.S. Customs on Staten Island without being stopped or the crate opened for inspection, although Customs reportedly has state-of-the-art x-ray and radioactivity detectors at this facility.

In a warehouse situation, a survey meter is non-directional and subject to false alarms. Portal detectors, or even a single collimated NaI detector, could be used as a first alarm, but a high-resolution

germanium detector should then be brought in to confirm the identification of a suspect source. A neutron detector can supplement the gamma-ray detectors.

Active interrogation, such as a high-energy x-ray cargo scan, is probably the only way to detect a well-shielded weapon inside a cargo container. However, an unshielded plutonium weapon emits about 10^5 neutrons and gamma rays per second [Fetter, 1990] and would be much easier to detect. From table 1, these radiations have mean free paths in air of the order of 100 m. A mobile detector for such a weapon could be carried on a golf cart for dockside inspection or on small watercraft for harbor inspection. It would contain one or more large germanium detectors and gas-filled neutron tubes along with battery power, electronics, and a computer-based MCA with analysis software. A similar system could be placed at border crossings and, with the addition of remote communication capabilities, under bridges leading to major ports, such as the Golden Gate Bridge in San Francisco and the Verrazano Bridge in New York.

A “dirty bomb” with enough activity to cause serious contamination would be easiest to detect. Small, cheap gamma-ray monitors with high enough thresholds to prevent frequent false alarms could be positioned at vulnerable locations in major cities and as perimeter monitors at nuclear facilities and military installations. Responders to such an alarm need to be equipped with NaI or germanium detectors and be trained to use them.

7. Available Point Detector Technologies

A. Gamma-Ray Detectors

Gamma-ray spectra from uranium and plutonium, illustrated in figure 5, start out showing sharp peaks with energies characteristic of the radioactive material. However, some of these gamma rays undergo interactions in the source and in the environment by which they lose energy

and are then no longer characteristic of the source material. Those gamma rays that reach the detector with their full energy can be completely absorbed, resulting in detection as a full-energy peak, or they can scatter and deposit only part of their energy. If the detector is large enough to have a significant probability of completely absorbing the scattered gamma rays, then the combined energy again results in a full-energy peak. A thin detector will have a small probability of complete absorption, and most of the detections will be in the continuum below the full-energy peak.

There are two commonly used classes of detectors for gamma rays in the energy range of emissions from nuclear materials, a) scintillation crystals coupled to photodiodes or photomultiplier (PM) tubes and b) semiconductor detectors. The most common scintillation detector is NaI(Tl) usually coupled to a PM tube (table 10). Other scintillators used in limited applications include thallium activated cesium iodide, CsI(Tl), and bismuth germanate, BGO. Plastic scintillators are used for large-area applications, such as portals, but they have little or no full-energy peak efficiency.

A common NaI configuration is a cylinder 3 in. in diameter by 3 in. long (7.5 cm diameter by 7.5 cm), but they can be made in many configurations and sizes. NaI detectors have relatively poor energy resolutions—at best about 50 keV (7.5%) for the 662 keV gamma rays from a ^{137}Cs calibration source. This limits their use in high-background situations or for unknown sources with many closely spaced peaks. Gamma-ray peaks from a weak source will be difficult to observe in a relatively high-background environment, and peaks that differ by a few percent in energy will be unresolved.

Semiconductor detectors were developed to overcome these limitations of scintillation detectors. With resolutions of typically 1.3 keV (0.2%) at 662 keV, Germanium semiconductor diodes (table 11) are the gold standard for gamma-ray detectors. This resolution allows precise

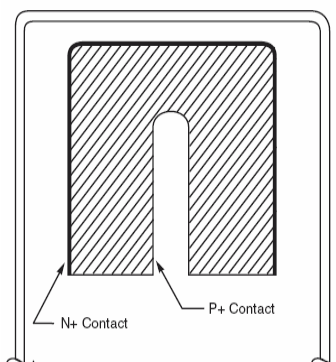


Figure 15. Cross section of a closed-end coaxial Ge detector [Canberra, 2004].

determination of peak energies, separation of close-lying peaks, and detection of weak peaks in the presence of a strong background. Germanium (Ge) detectors have the disadvantage that they must be operated at low temperatures (less than 100 K) to avoid excessive electronic noise. Normally, this is achieved by connecting the detector to a dewar containing liquid nitrogen (LN), which boils at 77 K. Small, hand-held dewars must be refilled daily, while larger dewars may last a week or more but are not easily portable. The detectors require several hours to cool down and, therefore, must be kept cool to be in a ready state^a. The requirement for a steady supply of LN can be a logistical problem in remote locations. Mechanical refrigerator coolers are also available, but these are more suited to fixed locations, since they are relatively heavy and require electric power. In a transportable detector, refrigerators could run off car batteries, but these would require frequent recharging.

^a The earlier lithium drifted detectors, Ge(Li), had to be kept cold at all times. Current detectors made with highly purified germanium, known as “Intrinsic” or “High-purity” germanium (HPGe) detectors can be allowed to warm up when not in use.

Large volume germanium detectors are cylindrical, with either a coaxial or closed-end coaxial diode configuration (figure 15), and can be made with volumes of several hundred cubic centimeters. They are often quoted as percent efficiency at 1332 keV relative to a 3x3 inch NaI detector. Ge detectors are currently available with diameters up to 9 cm and relative efficiencies greater than 100%.

Figure 16 shows calibration curves of peak detection efficiency versus energy for typical 32% relative efficiency p-type (GEM) and n-type (GMX) coaxial Ge detectors, measured using point gamma-ray sources 25 cm from the front face of the detectors. The maximum efficiency occurs at about 0.1 MeV with a value of approximately 0.3%. This is limited by the solid angle of the detector face and can be improved by using a larger area detector. The efficiency curve for GEM detectors drops off at lower energies due to attenuation in the outer dead layer of the detector and in the aluminum enclosure. The GMX curve extends the maximum efficiency to lower energy by using an n-type detector, which has a thinner dead layer, and by a thin beryllium entrance window in the aluminum enclosure. At higher energies, the efficiency drops off because the detectors cannot completely stop the high-energy photons. This can be improved by going to a thicker detector. Technical descriptions of Ge and other types of radiation detectors can be found in [Knoll, 2000].

There have been extensive efforts to develop room-temperature semiconductor detectors that can be used in place of germanium detectors. Cadmium telluride (CdTe), cadmium zinc telluride (CZT) and mercuric iodide (HgI) semiconductor diode detectors are currently available commercially (table 12). For CZT, best efforts to date have produced detectors with about

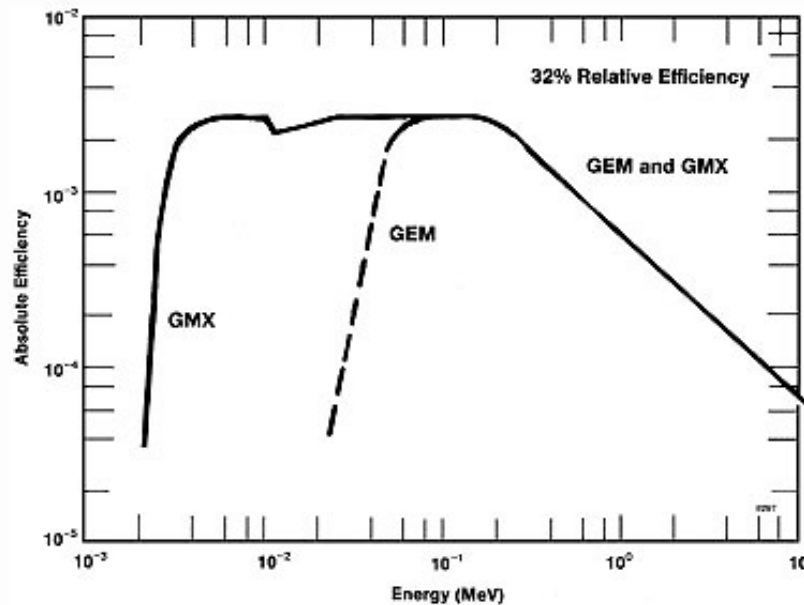


Figure 16. Calibration curves of peak detection efficiency versus gamma-ray energy for 32% relative efficiency coaxial Ge detectors [ORTEC, 2004]. The curve labeled GEM is for a standard p-type detector and GMX for an n-type detector with a thin Be window.

13 keV (2%) resolution at 662 keV. This is significantly better than NaI but still a factor of ten poorer than germanium detector resolutions. Commercially available CZT sizes are typically a square cm in area by 5 mm depth, which is not thick enough to provide useful full-energy peak

detection efficiencies in the several hundred keV to several MeV range characteristic of emissions from nuclear weapons. CdTe detectors are available with less than 1% resolution at 662 keV, but only for a small 3x3x1 mm detector. HgI detectors are available in larger sizes up to one cubic inch (16 cubic cm), but with poorer resolutions of about 25 keV (4%) at 662 keV.

B. Gamma-Ray Detector Electronics

Gamma-ray detectors require specialized electronics to convert the signal from the detector into a gamma-ray energy spectrum characteristic of the source. Figure 17 shows the basic components required. Traditionally, each of the modules shown represents a separate electronics box. Recently, however, several have been combined into compact low-power units convenient for surveys in the field.

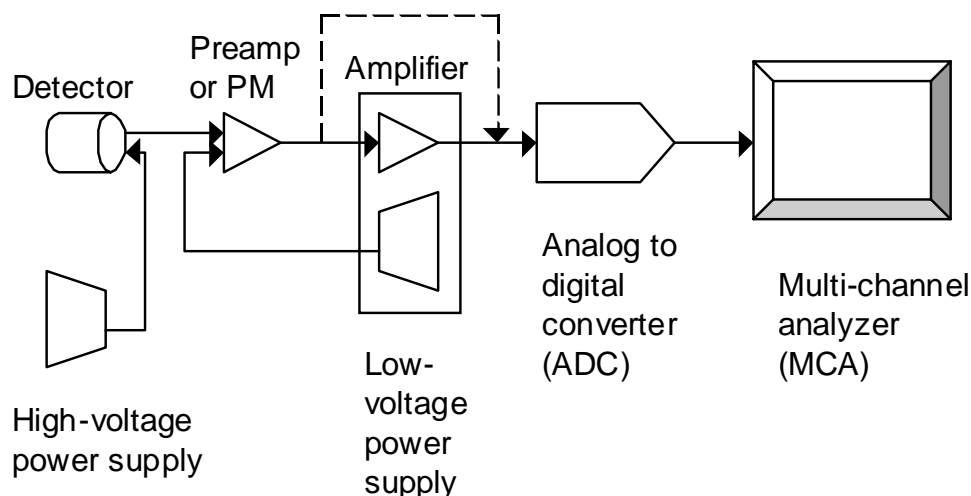









Figure 17. Schematic of typical gamma-ray detector electronics.

A DC high-voltage supply is required with output of a hundred to several thousand volts depending on the type and size of detector. The pulse from a semiconductor detector goes first to a preamplifier (preamp), which is usually attached to or in close proximity to the detector. The preamp output then goes to a module that amplifies and shapes the signal for input to the analog-to-digital converter (ADC). The amplifier module usually also contains a low-voltage power supply for the preamp. Scintillation detectors, such as NaI, are coupled to a photomultiplier (PM) tube that converts the scintillator light to an electronic pulse and contains up to a dozen multiplication stages. The PM output may require no further amplification and can be sent directly to the ADC. The output of the ADC is in digital form with a larger number corresponding to a higher pulse height, which in turn is proportional to the energy deposited in the detector. This number is sent to the multichannel analyzer (MCA), which builds up a spectrum consisting of counts per channel, with higher channels corresponding to higher energy. This spectrum is usually available as a real-time display. The MCA is normally computer based. It also contains software for applying energy and efficiency calibrations to the spectrum and for conducting a peak search and for calculating peak energies and intensities. It may also contain a

library of characteristic gamma-ray energies and intensities, for nuclides of interest, and software to identify peaks in the spectrum with the corresponding nuclide^a. The combination of ADC and MCA is sometimes referred to as a pulse-height analyzer (PHA).

^a A complete line of nuclear electronic modules is available from ORTEC, Oak Ridge, TN, or from Canberra Industries, Meriden, CT. (See table 10 for contact information.)

Table 10. Sodium Iodide Gamma-Ray Detectors

Illustration	Company	Size (diameter x length)	Dimensions/ Weight/ Power/ Cost
	Amptek Inc. 6 De Angelo Drive Bedford, MA. 01730 U.S.A. 781-275-2242 http://www.amptek.com	30x30 mm to 152 x 76 mm (1.2x1.2" to 6x3") Ruggedized assembly. Interfaces with MCA 8000A portable analyzer (See table 14)	Note a. 3x3 detector: 3" diam. x 10.5"/ 2 kg/ 200 mW/ \$7800 including MCA (laptop not included)
	Bicron/St. Gobain Solon, OH 440-248-7400 http://www.bicron.com	1x1, 2x2, 3x3" Polycrystalline up to 4x4x40" Other scintillators available include BaF3, BGO, CsI, GSO, LSO, and LaCl ₃	Note a.
	Berkeley Nucleonics San Rafael, CA 800-234-7858 http://www.berkeley-nucleonics.com	1.5x2, 2x2, 3x3" Also available as integrated probe (see table 14)	Note a.
	Canberra Industries Meriden, CT 203-238-2351 http://www.canberra.com	2x0.5, 2x2, 3x3" Other sizes available on request	Note a.
	ORTEC Oak Ridge, TN 800-251-9750 865-483-4411 http://www.ortec-online.com	1x1, 2x2, 3x3" Interfaces with portable analyzer. Also available as integrated probe (see table 14)	Note a. 3 x 14" overall/ 3 kg/ +12V at 20mA/\$731 (2x2), \$937 (3x3)
	Princeton Gamma-Tech Rocky Hill, NJ 800-229-7484 609-924-7310 http://www.pgt.com	1.5x2, 2x2, 3x3" Semirugged weather resistant assembly	Note a. 3x3" assembly: 4.5x13"/ 7 lb/ 0.5 mA @ 1 kV/ \$3700
	Scionix Utrecht, Netherlands In the USA: (407) 578-6469 http://www.scionixusa.com	Standard sizes 0.5 to 5" diameter Available with integrated photomultiplier and high voltage power supply	Note a.

^a NaI density is 3.67 g/cm³; for a standard 3x3 detector: volume = 347.5 cm³, weight = 1.275 kg (2.8 lb). Typical dimensions for a standard 3x3 detector with photomultiplier (PM) tube: 3.2 in diameter x 5.8 in. Typical weight: about 8 lb. Typical resolution: 7% at 662 keV, 5% at 1332 keV, typical cost < \$1,000 including PM tube and base.

Table 11. Portable Germanium Gamma-Ray Detectors

Illustration	Company	Relative Efficiency ^a	Resolution (keV)	Peak/Compton Ratio	Dimensions/Weight/Power/ Cost
	Canberra Industries Meriden, CT 203-238-2351 http://www.canberra.com	10-50%	0.8-1.2@122 keV (0.65-1.0%) 1.8-2.1@1332 keV (0.135-0.16%)	38-60	9x23"/ 16 lbs. With full 2.5 l dewar/ ~ \$29,750. Complete system with portable MCA, software and laptop ~ \$48,000
		55-100%	1.2-1.3@122 keV (1.0-1.1%) 1.8-2.1@1332 keV (0.135-0.16%)	60-80	
	ORTEC Oak Ridge, TN 800-251-9750 865-483-4411 http://www.ortec-online.com	10%	See table 14 The Detective	Table 14	Table 14
		15-53%	1.8-1.9@1332 keV (0.135-0.14%)	48-83	Dim. na/ 31 lbs with full 3 liter dewar/ \$27,662 for 50% detector with dewar
		63-118%	1.8-2.0@1332 keV (0.135-0.15%)	70-92	
	Princeton Gamma-Tech Rocky Hill, NJ 800-229-7484 609-924-7310 http://www.pgt.com	10-50%	0.8-1.0@122 keV (0.65-0.82%) 1.75-2.0@1332 keV (0.13-0.15%)	37-65	6x21" excl. handle/18 lbs with full 1.5 L dewar/ 250 mW/ \$39,000 with 50% detector
		55-100%	1.0-1.4@122 keV (0.8-1.15%) 1.95-2.3@1332 keV (0.15-0.18%)	64-75	

^a Efficiency at 1332 keV relative to a 3x3" NaI(Tl) detector with the source at 25 cm from the front face of the detector.

Table 12. Room Temperature Semiconductor Detectors

Illustration	Company	Detector Type Size (length x width x depth)	Resolution	Dimensions/ Weight/ Power/ Cost
	EURORAD Marne, France +33 (0) 1 56 86 11 49 http://www.eurorad.com <i>distributed by</i> Constellation Technology Largo, FL 727-547-0600 http://www.contech.com	CdZnTe Up to 5x5x2 mm	4-6.6% @ 122 keV	na
		CdTe Up to 5x5x1mm	<4% @ 122 keV	
		Integrated Pelletier cooler available.		
	eV Products Saxonburg, PA 724-352-5288 http://www.evproducts.com	CdZnTe (CZT) 4x4x2.5 mm up to 34x34x5 mm	3.7% @ 122 keV 2.5-3.5% @ 662 keV	SPEAR system (5x5x5 mm with preamp): 12mm diam. x 89mm/ <2 lb/ <50 mW
		Co-Planar Grid 10x10x5 mm to 15x15x7.5 mm		
		Custom sizes available		
	ORTEC Oak Ridge, TN 800-251-9750 865-483-4411 http://www.ortec-online.com	CdZnTe 5x5x5 mm	<3% @ 122 keV	na
		Portable detector probe, integrated with portable analyzer		
	Radiant Detector Technologies, LLC, Northridge, CA 818-709-2468 http://www.radiantdetectors.com	CdZnTe, 72 mm ³	5.7% @ 122 keV 1.8% @ 662 keV	na
		CdZnTe, 300 mm ³	<3% @ 662 keV	

na: information not available

Table 12. (continued) Room Temperature Semiconductor Detectors

Illustration	Company	Detector Type Size (length x width x depth)	Resolution	Dimensions/ Weight/ Power/ Cost
	EURORAD Marne, France +33 (0) 1 56 86 11 49 http://www.eurorad.com <i>distributed by</i> Constellation Technology Largo, FL 727-547-0600 http://www.contech.com	CdZnTe Up to 5x5x2 mm	4-6.6% @ 122 keV	na
		CdTe Up to 5x5x1mm	<4% @ 122 keV	
		Integrated Pelletier cooler available		
	eV Products Saxonburg, PA 724-352-5288 http://www.evproducts.com	CdZnTe (CZT) 4x4x2.5 mm up to 34x34x5 mm	3.7% @ 122 keV 2.5-3.5% @ 662 keV	SPEAR system (5x5x5 mm with preamp): 12mm diam. x 89mm/ <2 lb/ <50 mW
		Co-Planar Grid 10x10x5 mm to 15x15x7.5 mm		
		Custom sizes available		
	ORTEC Oak Ridge, TN 800-251-9750 865-483-4411 http://www.ortec-online.com	CdZnTe 5x5x5 mm	<3% @ 122 keV	na
		Portable detector probe, integrated with portable analyzer		
	Radiant Detector Technologies, LLC, Northridge, CA 818-709-2468 http://www.radiantdetectors.com	CdZnTe, 72 mm ³	5.7% @ 122 keV 1.8% @ 662 keV	na
		CdZnTe, 300 mm ³	<3% @ 662 keV	

na: information not available

C. Neutron Detectors

Neutron detectors (table 13) generally rely on converting the neutron energy to a charged particle that can then be more readily detected. The most common detectors are gas-filled



Figure 18. Gas-filled neutron detectors [Canberra, 2004A].



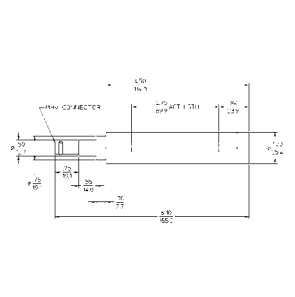

proportional counters, which consist of a sealed tube filled with boron fluoride (BF_3) or ^3He . These come in a variety of sizes and configurations (figure 18). A rare isotope of helium, ^3He is more expensive but has a higher detection probability, and ^3He tubes can be filled at high pressure to further increase the detection efficiency. BF_3 is a highly corrosive gas, so the tubes are generally filled at low pressure to decrease the probability of leakage. Gas-filled proportional counters are most sensitive to low-energy thermal neutrons (about 0.025 eV). The probability of detection decreases rapidly at higher energies. For detection of fission neutrons, with an average energy of about 1 MeV, these detectors need to be surrounded by a moderator, which slows the neutrons by multiple scattering reactions. Moderators

are usually materials, such as polyethylene, with high hydrogen content, since protons are the most efficient neutron scatterers.

Other types of neutron detectors consist of an isotope with high thermal-neutron reaction probability, such as ^6Li , combined with a plastic or glass fiber scintillator [NuSAFE, 2004.] These have the advantages that they can be made in any size and shape and have relatively high thermal-neutron detection efficiency.

A unique neutron detection technology is that of bubble detectors [Bubbletech, 2004.] These detectors consist of small droplets of superheated liquid inside a pressurized gel-like polymer matrix. Neutron interactions cause the droplets to expand into small gas bubbles, which remain trapped in the gel. Cumulative neutron exposure can be obtained simply by counting the bubbles. They can be erased and the detectors recycled by increasing the pressure. Real-time readout can be achieved by observing a change in the light transmission of the gel or by using an acoustic sensor to detect the bubble formation.

Table 13. Neutron Detectors

Illustration	Company	Detector Types	Efficiencies	Dimensions/ Weight/ Power/ Cost
	Bubble Technologies Chalk River, Ontario, Canada 613-589-2456 http://www.bubbletech.ca	Defender and Defender-XL passive bubble detectors: superheated liquid in gel matrix	Defender: 100 bubbles/ μ Sv Defender XL: 10,000 bubbles/ μ Sv	Defender: 7.9x0.75" diam./ 2.6 oz./ \$500 Defender XL: 13.8x1.6" diam./ 1.5 lb./ in development
	Canberra Industries Meriden, CT 203-238-2351 http://www.canberra.com	^3He filled tubes, cylindrical up to 5 cm diameter, or rectangular up to 15 mm thick	75% for thermal neutrons, up to 500 cps/nv ^a	up to 1 m long/
	LND, Inc. Oceanside, New York 516-678-6141 http://www.lndinc.com	^3He and BF_3 filled tubes, cylindrical up to 2" diameter or spherical, 4" diameter	Model 256109 SS ^3He filled 1267 cps/nv ^a	72" effect. length x 2" diam./ 1.359 kg/ 1000V/ \$2,800
			Model 25291 SS ^3He filled 10 cps/nv ^a	6.1" overall length, 2.75" effect. x 1" diam./ 150 g/ 1300V/ \$380
	NucSafe LLC Oak Ridge, TN 865-220-5050 http://www.nucsafe.com	^6Li filled glass fiber panels	15 to 50% for thermal neutrons	15x10x20"/20 lb/ 100-240 VAC 1.5 amp / \$6,628 up to 50x48x11.5"/ 450 lb/ 120 VAC 1.5 amp / \$21,469

^a nv = neutrons/cm²/s

D. Survey Meters and Portable MCAs



Figure 19.
Hand-held
survey meter
[Ludlum, 2004].

Small hand-held survey meters (figure 19) are available to detect gamma rays and neutrons separately or in combination (table 14). These generally are much less sensitive than the individual detectors discussed above and are useful only for strong sources at close range. Gamma-ray survey meters usually have small NaI detectors. Some may contain other sensors, such as CZT, but these are useful only for detecting low-energy gamma rays and x-rays from unshielded sources. Neutron survey meters usually contain gas-filled proportional counters inside a moderator.

Portable MCAs (table 14) generally combine the functions of an amplifier, ADC, MCA and power supply in a small integrated package, which interfaces with a handheld detector. Some recent models offer a complete package with a built in NaI, CZT or Ge detector and nuclide identification software.

Table 14. Portable MCAs and Survey Instruments

Illustration	Company	Model, Features	Detector Types	Dimensions/ Weight/ Power/ Lifetime/ Cost
	Amptek Inc. Bedford, MA. 781-275-2242 http://www.amptek.com	MCA8000A up to 16K data channels, 32K channel memory, high speed PC interface	Interfaces to CdZnTe (CZT) or scintillator detectors (NaI, CsI or BGO)	6.5x2.8x0./ <300g (0.7 lb)/ 2 AA batteries/ 24 hours/ \$3500
	Amptek Inc. Bedford, MA. 781-275-2242 http://www.amptek.com	GammaRad probe with DP4 digital pulse processor, up to 4K MCA channels, USB interface to PC.	Integrated 3x3" NaI detector, in ruggedized water and gas tight case.	na / USB Powered
	Berkeley Nucleonics Corp., San Rafael, CA 800-234-7858 http://www.berkeleynucleonics.com	SAM 935, up to 1024 channel MCA, LCD display, RS232 interface, isotope ID	Internal 1.5x2" NaI, optional external 2x2" or 3x3", internal ³ He neutron counter	12x8.5x2"/ 5 lb/ rechargeable NiMH battery/ 8 hours/ \$9,695 to \$24,950 depending on detector
	Berkeley Nucleonics Corp., San Rafael, CA 800-234-7858 http://www.berkeleynucleonics.com	PalmRAD 904, handheld meter with LCD digital readout	Internal GM tube	5.9x3.2x1.2"/ 8 oz/ 9-volt alkaline battery/ 24-200 hours (count rate dependent)
	Bubble Technologies Chalk River, Ontario, Canada 613-589-2456 http://www.bubbletech.ca	Microspec-2, handheld 256 channel MCA, nuclide ID, Microspec-3 includes GPS dose rate mapping	External gamma probe, neutron probe optional, interfaces to HP palmtop	10.3x6.3x2.7"/ 1.7 kg/ rechargeable batteries/ <14 hrs (M-2)/ 9 hrs (M-3)/ \$9910 (M-2), \$12,995 (M- 3)
	Canberra Industries Meriden, CT 203-238-2351 http://www.canberra.com	InSpector 1000, up to 4096 channel MCA, 512K channel memory, real-time nuclide ID, LCD display, USB interface	Up to 3x3" NaI probe, other sizes available	7.5x6.5x2.5"/ 4 lb/ rechargeable Li-ion battery/ 12 hours/ \$10,200

Table 14. (continued) Portable MCAs and Survey Instruments







Illustration	Company	Instrument, Features	Detector Types	Dimensions/ Weight/ Power/ Lifetime/ Cost
	D-tect Systems Santa Barbara, CA http://www.dtectsystems.com	Rad-ID, 4096 channel MCA, nuclide ID, 3.6 inch color LCD display	Internal 4 cm ² CZT array, 24.2 cm ³ NaI, 83 cm ³ ³ He neutron tube, GM tube	Dim. na/ 5.7 lb/ 3 D cell batteries/ 36 hours
	Ludlum Measurements Sweetwater, TX 800-622-0828 325-235-5494 http://www.ludlums.com	Model 3-97 with Model 44-38 GM probe, meter readout, many other configurations available	Internal 1x1" NaI, external GM probe	9.5x3.5x8.5"/ 4.4 lbs/ 2 D cell batteries/ typically 600 hr/
	ORTEC Oak Ridge, TN 800-251-9750 865-483-4411 http://www.ortec-online.com	The Detective internal mechanical cooler, nuclide ID software, LCD display, 8K channel digital MCA, stores up to 40 spectra	Internal Ge, 5 cm diam. x 3 cm (~ 10% relative efficiency), optional neutron detector	12.5x6.3x12.6"/ 23.3 lb/ 10-17 V DC, 30 W/ >3 hours on internal batteries/ \$55,000, \$65,000 with neutron detector
	ORTEC Oak Ridge, TN 800-251-9750 865-483-4411 http://www.ortec-online.com	MicroNOMAD up to 2K data channels, 32K memory, high speed PC interface	Interfaces to CZT or NaI detectors	2.8x2.8x8.4"/ 700 g (1.5 lb)/ 2 AA batteries/ 8 hours/
	ORTEC Oak Ridge, TN 800-251-9750 865-483-4411 http://www.ortec-online.com	DigiBase, PM tube base with integral Bias supply, amplifier, digital 1024 channel MCA and analysis software, USB interface	Integrated PM tube base for NaI detectors	6.3 cm diam. x 8 cm/10 oz/ <500 mA via USB/ na/ \$3995 (base only)
	ORTEC Oak Ridge, TN 800-251-9750 865-483-4411 http://www.ortec-online.com	DigiDart, MCA for portable HPGe systems, preamp and HV power supplies, spectroscopy amplifier, digital 16K MCA, nuclide ID, 23 16K spectra memory, LCD display	Interfaces to portable HPGe detectors	8x5x3"/ 1.9 lb/ rechargeable Li battery/ >9 hr/ \$9738

Table 14. (2nd continuation) Portable MCAs and Survey Instruments

Illustration	Company	Instrument, Features	Detector Types	Dimensions/ Weight/ Power/ Lifetime
	Quantrad Sensor Madison, WI 608-821-8360 http://www.quantradsensor.com	Ranger, Ranger Plus, built-in MCA and gamma reference library, LCD display, RS232 interface, submersible to 10m	1.125 x 2" NaI (Ranger), 0.5 x 4" ³ He neutron counter (Ranger Plus)	6.5x13.25x2.75"/ 5.9 lb/ rechargeable nickel battery, 150-200 mA/ 12 hours/
	TSA Systems, Ltd. Longmont, CO 970-535-9949 http://www.tsasystems.com	mMCA 430, 256 data channels, stores 159 gamma spectra and neutron counts, 128x32 pixel display	Internal 1x2" NaI, optional internal 1x0.2" LiI(Eu) neutron detector	10x4.75x4"/ 5 lb/ six AA batteries/8 hours (or rechargeable batteries/12 hours)/
	TSA Systems, Ltd. Longmont, CO 970-535-9949 http://www.tsasystems.com	MCA 465, 256 data channels, 14 spectra storage, 256x128 pixel display	Internal NaI or external probes	6.2x9.4x4.9"/ 7.5 lb/ rechargeable battery/12 hours/
	Exploranium Mississauga, Ontario Canada 905-670-7071 http://www.exploranium.com	The Identifier, GR-135, multiple detectors, nuclide ID	NaI, GM, optional: CZT, neutron	6.75x9x4"/ 4.5 lb/ 2 D cells/ 8-12 hours/
	Target Instruments Inc. Oak Ridge, TN 865 2208700 http://www.target-systems-gmbh.de	identiFinder, 1024 channel MCA, nuclide ID	NaI, optional: GM, CZT, neutron	23x9x7 cm/ 1 kg/ 4 AA cells/ 8 hours with rechargeable NIMH batteries/
	XRF Corporation Somerville, MA 617-623-7300 http://www.xrfcorp.com	ICS-4000, 4000 channel MCA, nuclide ID	CZT: 10x10x2 mm, 1.6% @ 662 keV, built in recharger	10x3.4x1.2"/ 1.5 lb/ 6.6V Li/ up to 7 hr/

E. Portals and Search Systems

Pedestrian and vehicle portals for detecting nuclear materials combine large plastic scintillators or NaI gamma-ray detectors with gas-filled neutron detectors. These are contained in pillars similar in configuration to airport metal detectors (table 15). Nuclear search systems typically contain large NaI detectors and ^3He neutron tubes mounted in a van or cartop container. They have been in use for some time by the U.S. Department of Energy and have recently become commercially available (table 15).

8. Imaging Technologies



Figure 20. GammaCamTM image of a gamma-ray source inside a truck [EDO, 2004].

Imaging detectors (table 16) can be either passive, looking at the natural emissions from the target material, or active, using high-energy x-rays or gamma rays to image the target. Imaging can improve the signal to background ratio, since the target generally covers a small field of view while the background tends to come from all directions. Astronomers have led the development of passive imaging techniques for gamma-ray astronomy. Coded-aperture imaging uses a computer designed mask and software reconstruction to produce an image [Ziock, 2003]. It works best in the energy range up to 300 keV, above which it is difficult to stop gamma rays with a mask. Compton imaging, which works without a mask and uses the physics of gamma-ray scattering in the detector to reconstruct an image, has been used to detect gamma rays up to 30 MeV [COMPTEL, 2003]. The GammaCamTM imaging system (figure 20) employs the coded aperture technique. It has been used by DOE to image relatively high-activity sources at the Hanford, WA facility and at Argonne National Laboratory, Argonne, IL [EM-DOE, 1998]. This technology is particularly good for imaging hot spots in a high radiation background, but would be less capable for imaging the relatively weak attenuated signal from a shielded weapon. Current passive imaging systems are relatively complex and limited in efficiency.

Active imaging systems, using a high-energy x-ray, gamma-ray or neutron source, can penetrate low atomic number materials to obtain a transmission image of embedded uranium or plutonium, which are very dense materials. They may also be used to image stimulated emissions of neutrons and gamma rays, which are induced in nuclear materials by the interrogation source radiation. These systems typically employ a scanning procedure in which the source and detectors move together along either side of the vehicle being inspected. The EAGLE[®] cargo inspection system, which employs active imaging using transmission x-ray technology, is used by the U.S. Customs service for inspecting trucks or cargo containers (figure 21). This system uses high-energy X- rays of 3 or 6 MeV, which can penetrate up to 30 cm of steel and image a highly shielded weapon. The manufacturer has signed a CRADA^a with two DOE laboratories to use this system for imaging photo-fission induced neutrons and gamma rays from nuclear materials. The VACISTM transmission gamma-ray imaging system uses high-energy gamma rays

^a CRADA: Cooperative Research and Development Agreement.

from a ^{137}Cs or ^{60}Co source to image a vehicle (figure 22). The Shaped-EnergyTM x-ray system uses a 220 or 450 keV x-ray beam and detects both transmission and backscatter x-rays from the cargo to form dual sided images. This system can simultaneously detect gamma rays and neutrons emitted from the cargo during the scan.

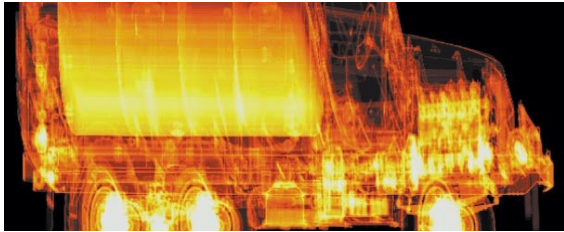


Figure 21. Truck image using the Eagle[®] cargo inspection system [Aracor, 2004].

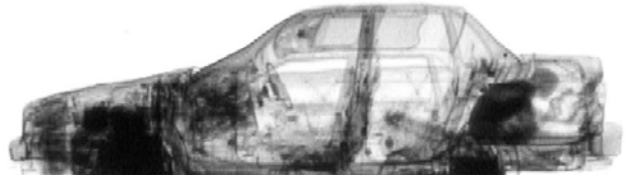






Figure 22. Car image using the VACISTM vehicle inspection system [SAIC, 2004].

Table 15. Vehicle Portals and Search Systems

Illustration	Company	Instrument, Features	Detector Types	Dimensions/ Weight/ Power/ Cost/ Lifetime
	Canberra Industries Meriden, CT 203-238-2351 http://www.canberra.com	RADsentry, for vehicles up to 2 m or cargo containers up to 4 m. Also rail and pedestrian configurations	plastic scintillator, 975 in ² . ³ He optional neutron detectors, 59x2" diam., operating temp. -40 to +50C	73x28.5x9.5" ea./ 559 lb./ 24VDC, 120/220 VAC/ \$23,000 to \$90,000
	ORTEC Oak Ridge, TN 800-251-9750 865-483-4411 http://www.ortec-online.com	Car-top search system, built-in power supply, MCA, GPS mapping, USB interface to laptop computer, NaI spectral analysis, count rate vs. time or position	4x4x16" NaI (10% resolution @ 662 keV) two ³ He neutron tubes 50x2.5 cm diam. with 4" polyethylene moderator	12V battery power
	Thermo-Electron Corporation Waltham, MA 781-622-1000 http://www.thermo.com	Safety-Guard™ II vehicle portal inspection system	Up to 8 gamma or 4 gamma and 4 neutron, optional speed and occupancy sensors, ethernet interface	72x18x12"/ 154 kg/ \$21,700 to 65,800
		Safety-Guard™ I conveyor system for package monitoring	gamma (two plastic scintillators, optional two neutron (³ He gas filled), optional speed and occupancy sensors, ethernet interface	30x17x8"/ 91 kg/ \$17,450 to \$23,250
	TSA Systems, Ltd. Longmont, CO 970-535-9949 http://www.tsasystems.com	Model VM250/ VM250AGN, based on Los Alamos design, optional heaters and insulation	gamma (two plastic scintillators, 6x30x1.5", per column), optional neutron (four 2x36" ³ He)	VM250: 10x10x96 or 120" ea./ 136 kg VM250AGN, 8x26x96 or 120"/ 273 kg/ battery powered/ >24 half-life

na: information not available

Table 16. X-Ray and Gamma-Ray Imagers

Illustration	Company	Instrument, Features	Detector Types	Dimensions/ Weight/ Power/ Cost
	ARACOR Sunnyvale, CA 408-733-7780 http://www.aracor.com	EAGLE [®] mobile cargo inspection system uses high-energy x-rays (3 or 6 MeV) and produces a transmission image	na	na
	AS&E Billerica, MA 978-262-8700 www.as-e.com	Shaped-Energy [™] mobile cargo inspection system uses 220 or 450 keV x-rays and produces both transmission and backscatter images	na	na
	EDO Corporation New York, NY 212-716-2050 http://www.nycedo.com	GammaCam [™] portable gamma-ray imager, 25 or 50 degree field-of-view, 1.2 or 2.6 degree resolution, 1 μ R dose sensitivity, interfaces to PC	High-density Terbium-activated scintillating glass	19x10x15"/ 60 lb/ 100-240 VAC/ \$180,000
	SAIC San Diego, CA 858-826-9738 www.saic.com	VACIS [™] mobile cargo inspection system uses high-energy gamma-ray sources and produces a transmission image	na	na

na: information not available

9. New Detector Technologies

A. Integrated Detection Systems

Most current and developmental nuclear detection systems display the information they capture on or near the units. However, wireless connectivity to remote locations, such as command centers, is increasingly desired and possible. One example of a new gamma-ray detection system is shown in figure 23. It contains a NaI detector and associated electronics, plus a radio that can transmit information on the output of the detector, all within a small case. This system was employed at the Athens Olympics in 2004. It can also be outfitted with sensors for chemical and biological detection. The integration of multiple sensors into one detection system permits sharing of the power supply, computer and communications sub-systems. It also reduces the number of systems that must be bought, maintained and used by field personnel.

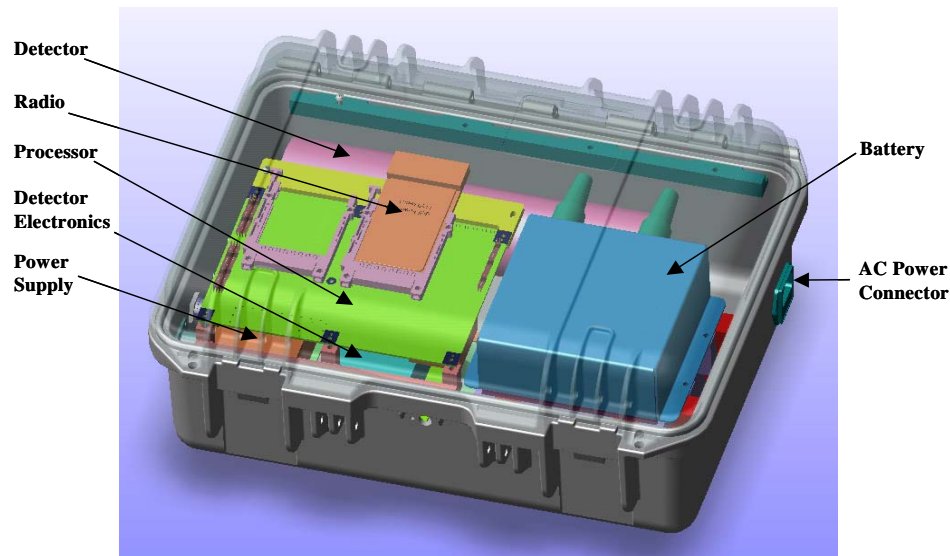


Figure 23. Drawing of the Mobile Defender wireless gamma ray detection system used in the 2004 Olympics [Soflinx, 2004].

A unique portable system, the PIRATE, shown in figure 24, provides a compact, secure wireless communication platform for hazardous material analysis. It can be equipped with sensors for nuclear, chemical or biological materials, GPS, a graphical interface and image recognition software.



Figure 24. The PIRATE portable WMD analysis platform. The sensors and communication transmitter are installed in the suitcase-like container [KC, 2004].

B. Detector Technologies in Development

There is much ongoing research on room temperature semiconductor detectors for gamma rays, which is the subject of a biannual workshop [RTSD, 2001]. This research focuses on two main approaches, a) to grow larger single crystals in order to be able to make useful detectors for gamma rays in the several hundred keV to several MeV range and b) to obtain uniform charge collection efficiency in order to improve the full-energy peak resolution. Much of the effort has been focused on CZT, but progress has been slow.

Another technology that shows promise for gamma-ray detection uses high-pressure xenon detectors [Mirmar, 2003]. A new scintillator, $\text{LaCl}_3(\text{Ce})$, is available with properties similar to NaI, but with superior resolution of less than 4% at 662 keV for a 1" diameter x 1" crystal [St. Gobain, 2004]. Other new scintillators, such as LaBr_3 , are under development with resolutions better than 3%, which is less than half that of NaI detectors [Shaw, 2003].

A very compact, low-power mechanically-cooled Ge detector system is under development using a miniature Stirling-cycle cooler. This instrument is designed for long shelf-life in the field and contains peak analysis software and nuclide identification using a stored gamma-ray library. The prototype can operate up to nine hours using a rechargeable Li ion battery [Madden, 2003].

Ongoing research in neutron detectors is focused on solid-state detectors to replace gas-filled tubes [McGregor, 2003; Phillips, 2002]. The approach here is to make use of neutron-capture reactions to convert the neutron into an energetic charged particle, which can then be detected by solid-state detectors. A converter material is used, such as ^{10}B , which has a high thermal-

neutron capture cross-section and emits energetic charged particles following capture. Efficiencies as high as 30-50% can be achieved by the deposition of ^{10}B in grooves or dimples in the detector surface [McGregor, 2003].

Compact Compton and coded aperture gamma-ray imaging systems are being developed using segmented Germanium detectors to obtain good sensitivity, high energy resolution, and good angular resolution [Vetter, 2003], [Hull, 2003]. An innovative imaging technology under development uses scattering of cosmic-ray muons to image high atomic number materials, such as uranium and plutonium [Borodzin, 2003], [Physics Today, 2003]. The developers estimate that a border detection system could be built to detect a 10 cm cube of uranium in one minute.

Active interrogation, using a pulsed neutron source, is being investigated as a means of detecting highly shielded HEU. Delayed high-energy gamma rays in the range of 2.5 to 4.0 MeV are the result of the decay of induced fission products. These are highly penetrating, and occur at energies where the interference from natural background is low. Large detector arrays can be used to locate the source inside a cargo container [Slaughter, 2003]. A similar device is being developed using interrogation by high-energy photons from a linear accelerator [Jones, 2003]. Another pulsed-neutron interrogation device under investigation uses delayed epithermal (eV energy) induced neutrons to detect shielded nuclear materials [Melton, 2003].

10. Summary and Conclusions

A small nuclear weapon, such as that dropped on Hiroshima during World War II, could deliver a lethal dose of radiation and level unreinforced buildings out to a km or more. A radiological weapon used to disperse radioactive material in a densely populated area could result in hazardous doses, if the population is not promptly evacuated. The extent of the affected area would be hard to predict due to variable wind patterns and the influence of large buildings on particle dispersion patterns. The resulting contamination could render affected areas temporarily uninhabitable and require costly cleanup operations.

The principle fissionable materials used in nuclear weapons are highly enriched uranium and weapons grade plutonium. Radiological weapons may contain a variety of industrial or medical radioactive sources along with chemical explosives or other dispersion methods, such as aerosols. Even a small amount of radioactive material in the debris after a chemical explosion could complicate cleanup of the site.

The primary observables from nuclear weapons, nuclear materials and radiological materials are gamma rays and neutrons. Both have a mean free path in air of the order of a hundred meters, which means they are not observable by high-flying aircraft or by satellite. There is also a substantial natural background of both gamma rays and neutrons, which limits the detectability of contraband nuclear or radiological materials. The signal from a point source of gamma rays or neutrons decreases with the inverse square of the range while the background remains constant. This limits the distance at which the source can be detected above the statistical noise in the background. Small hand-held detectors are useful out to a few meters at best. With large area efficient detectors, unshielded nuclear weapons or nuclear materials are detectable out to ranges of a few tens of meters.

Gamma-ray imaging detectors can be used to locate a source and reduce the interference of the background, which is usually non-local. However, current passive imaging systems are complex and relatively inefficient. Active imaging systems can efficiently image large containers

at close range using high-energy x-rays or neutrons to obtain a transmission image or to stimulate gamma-ray and neutron emissions from nuclear materials.

Plutonium weapons are generally detectable by their neutron emissions. These can be shielded by large amounts of neutron moderating materials combined with thermal neutron capture materials. The most efficient moderators contain significant amounts of hydrogen in their molecular structure, such as water, paraffin, or polyethylene. Highly enriched uranium weapons, in principle, emit few neutrons and only low-energy gamma rays, which are easily blocked by thin lead shields. However, other isotopes of uranium which emit high-energy penetrating gamma rays that require many cm of lead to shield are typically present in these weapons. Active interrogation by beams of high-energy x-rays or neutrons can best be used to detect highly enriched uranium or plutonium that is well shielded from passive detectors. Radiological weapons materials are highly radioactive and relatively easy to detect using passive gamma-ray detectors.

For nuclear detectors, size still matters. The physics of the detection process requires detector volumes of a few hundred cubic centimeters for useful detection of gamma rays and neutrons from nuclear weapons. It takes a detector several centimeters thick to stop the characteristic gamma rays from nuclear materials. Fission energy neutrons must be reduced to thermal or near-thermal energies for efficient detection, which requires several centimeters of moderator in or around the neutron detector.

Pulse-height analyzers combined with specialized nuclear electronics are used to display an energy spectrum from a gamma-ray detector. Characteristic peaks in the spectrum can be recognized visually or by use of analysis software to identify the gamma-ray emitting material.

Germanium semiconductor diodes are still the “Gold Standard” for detection and identification of gamma rays from nuclear material. They are available with volumes of several hundred cm³ and have excellent peak resolutions of about 0.2%. This allows the characteristic gamma rays from these materials to be detected above the environmental background, thus providing positive identification of the source. However, Ge detectors must be cooled to temperatures below 100 K, which requires liquid nitrogen cooling or electric power to operate a mechanical cooler. Room temperature semiconductor detectors, such as CZT, are currently limited to a few cm³ in size and 2-3% in resolution. Large efficient NaI scintillator detectors are available, which operate at room temperature, but with limited gamma-ray resolution of about 7.5%. However, newer scintillators with improved resolution are under development.

Neutrons must be moderated to thermal energies for efficient detection. Efficient neutron detectors combine a moderator with a material that captures the neutron and emits charged particles for detection. He³ or BF₃ gas-filled proportional counters are still the standard for neutron detection, but other technologies, such as ⁶Li glass fibers and bubble detectors, may be useful in some applications. Detectors under development combine a neutron capture material with a semiconductor detector for compact and efficient neutron detection.

Protection against nuclear and radiological weapons requires a suite of detectors including active interrogation for cargo containers, stationary active or passive detectors for scanning smaller containers, large gamma-ray and neutron detectors at ports of entry, and handheld detectors for inspecting suspicious packages. Small gamma-ray monitors in heavily populated areas could provide valuable warning of a radiological attack, giving time to evacuate the area before significant doses are acquired. First responders should be equipped with handheld detectors and trained to use them and to interpret the results.

There are many possible sources of false alarms in the environment due to terrestrial, atmospheric and cosmic-ray induced backgrounds, as well as man-made sources for medical and industrial uses. Responding to false alarms can be time consuming and expensive. If a detector system is subject to excessive false alarms it will eventually tend to be ignored. The only way to reduce these to an acceptable minimum is to have the right equipment in the hands of trained and experienced inspectors. Calibration curves and receiver operator characteristics (Appendix A) should be developed for all fielded nuclear detectors in the types of scenarios that their users are most likely to encounter.

Appendix A. Calibration and Operating Curves

Regardless of the signature being detected, there are some fundamental aspects of analytical procedures that remain unchanged for all detection technologies. Prime among them is the need for and use of a calibration curve that quantitatively relates the signal from the detector in the system to the quantity of interest, usually the intensity of radiation or the number of molecules in an analytical situation. A generic linear calibration curve is sketched in figure A.1.

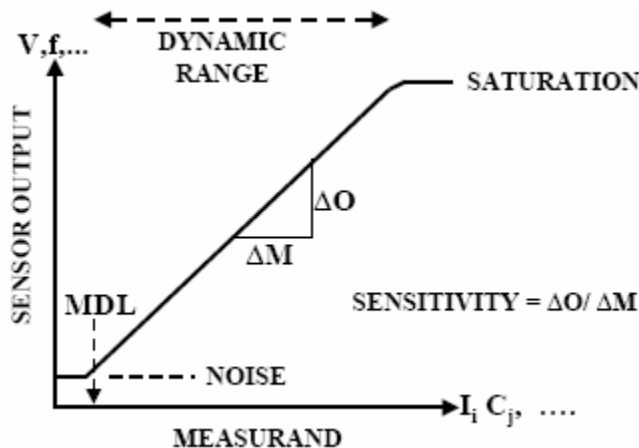


Figure A.1. A generic calibration curve relating the output of a sensor or detector to the value of the quantity of interest (the measurand).

Nonlinear calibration curves are not uncommon. The detector output, possibly a voltage V or a frequency f , is quantitatively related to the measurement goal, with the intensity I of the i 'th radiation or the concentration C of the j 'th chemical, indicated in the figure. Implicit in this calibration curve is the specificity of the analytical system. That is, the instrument uses some spectral or other feature that is uniquely related to the material of interest. Interferences from other materials are a common problem. Sensitivity is a different concept from specificity and is defined as the rate at which the signal changes relative to changes in the analyte, namely $\Delta O / \Delta M$, the slope of the calibration curve. Sensitivity is commonly used to mean the lowest concentration of a material that an instrument can detect. However, the phrase "minimum detectable limit" (MDL) should be used for the threshold value. It depends on the combination of a specific instrument, the material of interest and the employment scenario. The dynamic range of the system is the range of the measurand over which an analytical instrument operates, before some factor limits performance. High sensitivities tend to go with narrow dynamic ranges, and vice versa.

The minimum detectable limit (MDL) for the combination of a specific instrument and material of interest, indicated in figure A.1, is the least amount of the material that can be detected. The calibration curve clearly indicates how an increase in the noise will give an apparent signal that falsely indicates a value for the measurand that is above the MDL. In such a case, the increased noise leads to a false positive report of the presence of the measurand. The noise floor of an analytical instrument determines the MDL for the particular material. There are

many sources of noise, which can enter at each step in the detection process of an analytical instrument. Figure A.2 indicates the sources of noise, which must be considered by both the designers and the users of analytical devices. Noise can arrive with the signal or sample and, thus, may be unavoidable. However, noise is sometimes introduced from the outside somewhere else in the chain of events in an instrument, or by the instrument itself, for example, electrical or mechanical noise.

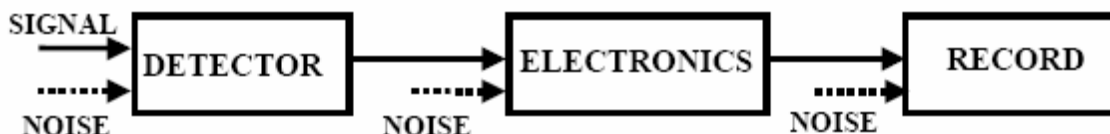


Figure A.2. The multi-step conversion of incident energy into information, with the potential injection of noise at and within all stages.

Interferants produce unwanted signals that can cause two problems. First, they can serve to provide an enhanced background noise that limits the ability to detect low levels of something of interest. Second, they can interfere with the signals from the material of interest. Interferants may or may not be related to the materials that are being sought. Radioactivity from nature, including isotopes in rocks, pollution from man-made sources, and cosmic rays, provide backgrounds above which the gamma rays or neutrons from suspect objects must be measured.

The calibration curve is essentially a detailed performance specification of a detection technology. It is generally obtained by measurements free of interferants and extraneous sources of background. The resulting calibration is usually stored in the analysis system computer, which uses it to convert the received data signal to the desired information. Determination of a calibration curve is challenging since it requires establishing and independently ascertaining the measurand, for example, 2 grams of enriched uranium inside an aluminum can of certain characteristics. Very often, standard samples are used for the calibration of detection technologies. Many of these are available from the National Institute for Standards and Technology (NIST) in Gaithersburg, MD, or from companies that sell secondary standards traceable to NIST standards.

Ideally, the calibration curve is scenario independent. However, substances that interfere with the measurement of interest and variable backgrounds in some locales where a detection technology is used tend to modify the calibration curve. In many cases, the calibration curve is sensitive to temperature or some other ambient factor. Then, the analysis system computer also has to perform calculations to compensate for extraneous effects that degrade the accuracy of the analytical determination. These are measured by other sensors in the system, such as temperature and humidity monitors.

This general calibration curve applies to various instruments for detection of nuclear and other materials. In the case of radiation from nuclear materials, be it natural radioactivity or stimulated neutron, gamma-ray, or x-ray signals from a nuclear device, the measurand is the intensity and the detector output is generally numbers of counts or an energy spectrum. The efficiency of the detector system, which depends in turn on many material and geometrical factors, will determine how well the system “uses” the information in the available radiation. The minimum detectable limit for nuclear detectors is often taken to be three times the standard

deviation of the noise. That standard deviation is the reciprocal of the square root of the number of counts or, for spectra, the number of counts per energy region of interest.

Detection technologies and associated instruments are like any system. They will not operate properly for long times without appropriate attention. Testing of the operation of an instrument needs to be done after it is manufactured, at the beginning of use and during its service lifetime. The most fundamental test of an instrument is to determine if it will simply turn on. Indicator lights are usually built into an instrument to give such notice. The next level is determination of whether or not an instrument operates. Again, it is sometimes possible to provide indications of such a function. It is more difficult to ascertain if an instrument works properly. That is, will the system give the correct answer? To learn this generally requires introduction of a known value of the measurand and the observation of a correct readout. Small sealed radiation sources containing a known amount of a particular radionuclide are commonly used to check nuclear detection devices. Very few instruments have built-in test capabilities that are a good facsimile of the analyte of interest.

It should be noted that most commercial analytical devices and systems are subject to procedural standards that serve to insure their proper operation. Standards published by the International Organization for Standardization (ISO) and other organizations must be satisfied by analytical services in manufacturing, medical, environmental and other industries. The technologies used to detect NRWMD can be subject to the same kind of constraints. Such standards should not be confused with the standard samples that are often employed to calibrate analytical techniques.

It is important to appreciate the difference between detection of a material for WMD and the quantification of that material. Both are operationally important. The detection question is binary: is the material present within the range of the instrument being used? However, making that decision, based on the output of the instrument, can be both complex and uncertain. That is usually the case for the detection of NRWMD, because either there is very little material in the first place or else a larger amount is more distant from the instrument. Non-subjective and, ideally, operator independent criteria should be applied to make a yes-no decision about a detection.

There are two situations regarding the presence or absence of the material of interest within the measurement range of a particular instrument. The first has to do with whether the material is actually present or not. The second has to do with whether the instrument says it is there or not. Hence, there is a two by two matrix of possibilities, as illustrated in figure A.3

		ACTUAL (IN)	
		POSITIVE	NEGATIVE
SIGNAL (OUT)	POS.	TPF	FPF
	NEG.	FNF	TNF

Figure A.3. The “truth table” for the signal output of an instrument in response to input from samples that either have or do not have the material of interest.

The results for each of the four cases are stated in terms of fractions normalized to unity. If the sample is actually present at the input of the instrument, the case called “positive”, then the instrument output may say it is there (the True Positive Fraction or TPF) or not there (the False Negative Fraction or FNF). TPF and FNF sum to one, because there are only two potential outcomes of the measurement. If the material is absent from the input, the “negative” case, then again, the instrument may indicate either, that it is there (the False Positive Fraction or FPF) or not (the True Negative Fraction or TNF). Again, FPF and TNF add to one. In an ideal situation, there would be no False Negatives or False Positives, and True Positives and True negatives would each occur 100% of the time when the sample is present or absent, respectively. However the presence of noise in the output of the detection instrument blurs the situation.

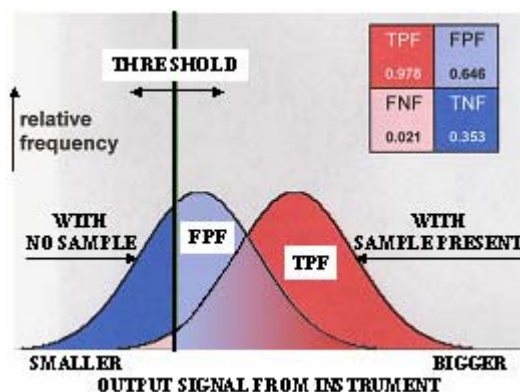


Figure A.4. Distributions of the signals from a detection technology for two cases: without and without the material of interest being present.

In figure A.4, there is a curve to the right indicating the output distribution for repeated measurements with a sample present and another to the left for a second group of measurements with no sample. Each has a width dependent on the noise in the system. The part of each distribution above the chosen threshold used to declare a positive detection event is critical to the

utility of the system. In the case shown, the True Positive Fraction is large (97.8%). This means that the system will miss an actual sample only about 2.2% of the time. The False Positive Fraction is intermediate in size (64.6%). This means that about two-thirds of the time when no sample is there, the system will say that there is a sample present. This is highly undesirable, since in an airport screening situation, a nuclear sensor might falsely indicate that it is necessary to detain the majority of passengers who have no nuclear materials.

Figure A.4 makes it clear why reduction in the noise in a detection system is highly desirable. Less noise gives narrower distributions, which will yield higher TPF because less of the low output tail of the sample-present distribution will be found to the left of the threshold. Alternatively, the threshold could be raised, maintaining the same True Positive Fraction, but reducing the False Positive Fraction. If there is actually no material of interest present in the sample, then the two distributions for no-sample and sample are coincident, and the TPF and FPF are equal for any setting of the threshold. At the other extreme, if there is enough of the material in the sample, an output signal large enough to entirely separate the two distributions will result. That is, the distribution with a sample present will move to the right, away from that with no sample. Then, setting the threshold between the two distributions will give a True Positive Fraction of unity and a False Positive Fraction of zero, the ideal situation.

Referring back to the calibration curve in figure A.1, when the measurand is well below the MDL, the sample and no-sample distributions are coincident. When the measurand is near the MDL, then the two distributions are distinct but strongly overlapping. They are separate, that is, non-overlapping, when the value of the measurand is sufficiently above the MDL, depending on the size of the noise. These three cases lead to three distinct curves if the True Positive and False Positive Fractions are plotted against each other. Such a curve is called, for historical reasons, a “Receiver Operating Characteristic”, or ROC curve. Possible ROC curves are shown in figure A.5 for the ideal case (separate distributions), the worst case (coincident distributions) and the common intermediate case (overlapping but distinct distributions). The area under the ROC curve is a measure of the “goodness” of the detector system. A perfect detector system has an

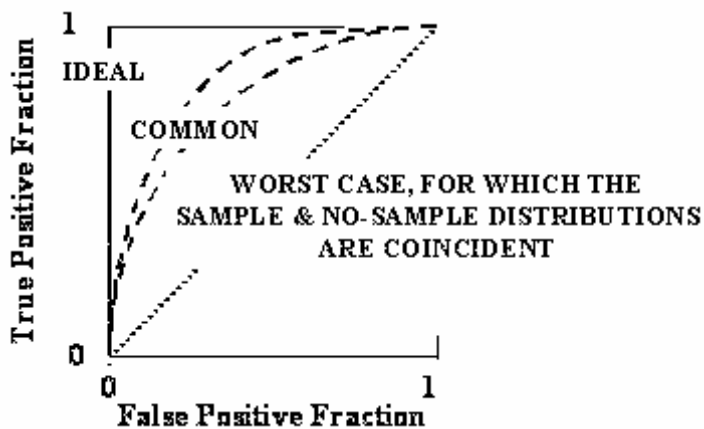


Figure A.5. ROC curves for the two extremes and the common intermediate cases when an instrument is being used near its minimum detection limit to make a present or not-present decision.

area of one. A detector system with an area of one half is useless for the yes-no question of the presence of material. All detector systems fall between these two limits. The essential point of

the ROC curve is that the goodness of a detector system can only be evaluated by extensive measurements in the environment in which that system will be used.

ROC curves grew out of attempts to detect weak returns in radar systems, but they are quite general and no less applicable to detection technologies for WMD. It is very rare to find ROC curves in the ordinary literature on analytical instruments or devices for detecting WMD. However, they provide a systematic, non-subjective means to assess the performance and risk in using a detection technology in a binary fashion. It would be helpful for evaluation of WMD detection technologies if ROC curves for these systems were to become a standard by which to judge detector system utility.

There are three types of information desired from detection technologies: (a) whether or not a material of interest is present, (b) determination of the amount and (c) its identification. The yes-no detection scenario for the presence of NRWMD materials is important both before and after the use of a device. If such materials are detected before an event, then appropriate actions might be taken to prevent the use of the dangerous materials. If residues from nuclear or explosive materials are detected after an event, information on the kinds and amounts of materials must be sought. This has uses that range from deciding what to do next for public safety to forensic determination of who is responsible for the attack.

If the amount of the material of interest in a sample is well above the MDL, the output signal from the sensors and the system will be well above the noise floor. Then, it is possible to use the calibration curve to quantify the amount of material. In this case, the detection is certain, and the question is how much of the material is present. Quantifying the amount of WMD material is very useful because it can dictate immediate actions. If a large amount of nuclear material or explosive is found, it would indicate a course of action different from the detection of trace or small amounts of the same material. Quantification of nuclear materials is useful well after their dispersion because they can be difficult to cleanup, they are slow to move in the environment and they can have very long half lives.

Knowing specifically what is being dealt with will determine the actions of emergency and medical personnel. This knowledge is critical both to patients and care givers in the aftermath of an attack. Determination of what material is present may require equipment different from that used for detection and quantification. For example, a Geiger counter will give a useful counting rate, but no indication of the type of material emitting the measured radiation. In that case, it is necessary to use some spectral instrument, such as a germanium detector with a multi-channel analyzer, to see from the peaks in the spectrum what is the source of the radiation. Quantification and identification are both necessary to determine what actions are needed before the affected facilities can be returned to use.

Appendix B. Practical Factors

Many factors have to be considered by managers responsible for buying detection technologies for WMD. Most of them are applicable to most instruments for detecting and quantifying materials and devices for WMD. Below is a list of important factors in the form of questions that should be answered in preparation for a purchase of detection instruments:

1. What has to be measured and over what range of values?
2. What are the options for making the needed measurements?
3. What are the advantages and disadvantages of each option?
4. How long has each technology been on the market?
5. How many of each type of instrument have been sold?
6. Where and when will the measurements be needed?
7. What MDL and accuracy are needed?
8. How does the MDL compare with thresholds for damage to people and things?
9. Who will be making the measurements?
10. Are the instruments portable?
11. What kind of power is needed, alternating current or batteries?
12. If batteries are used, how long will the instrument operate fully on one set?
13. What is the size, weight, required power, ruggedness, etc. of candidate instruments?
14. What are the ranges of temperature, humidity, etc. over which an instrument will work?
15. How long does it take to set up or warm up the potential instruments?
16. How fast must the measurements be made?
17. How fast can the measurements be made, analyzed and communicated?
18. How often might the measurements be made?
19. What interferences might be encountered?
20. How much do the instruments cost?
21. How many instruments will be required?
22. How long does it take to get replacements?
23. What supplies are needed for the instruments?
24. Who makes replacement parts and sells supplies?
25. How much do the supplies cost?
26. How long does it take to get the supplies?
27. What is the shelf life of the technologies and the supplies?
28. Is recalibration in a central facility required, and how often?
29. What education level is needed for operators?
30. How much operator training is needed?
31. Is recertification of operators needed, and how often?
33. What is the reputation of the detection technology?
34. What is the reputation of the sellers of instruments and associated parts and supplies?
35. What is the reputation of the companies that provide training for operators?
36. What are the case histories of the actual use of specific instruments in the field?

Many other questions can be asked. The set of relevant questions, and their relative importance, is highly dependent on the organization that will be using the instruments and the

scenarios it expects to encounter. Managers responsible for procurement decisions for WMD detection technologies are faced with complex choices.

The gathering of information and the assessment of each alternative solution, or mixes of solutions, are difficult. Getting the information upon which overall assessments and procurement decisions will be based requires contacting a large number of companies and others. Performing the assessments, given the available information, is not easy because of the range of options and potential scenarios for use. Training is needed for the hands-on users of detection technologies, for analysts who might examine and integrate the information from detection technologies, and for the ultimate users of the information. Failure to properly employ an instrument will lead to problems that range from obtaining no information to getting wrong answers, possibly without realizing that they are in error. Analysts must know the limitations of, and uncertainties in the information that comes from various instruments in order to properly assess its importance. The managers who make decisions based on the output of detection technologies will usually not have time to deal with questions of calibration and other details. However, they should have some idea of the basics of a detection technology in order to avoid ascribing undue importance to information from such sources.

Despite the often high cost of advanced instruments, even hand held devices, people are usually the most costly part of an overall capability. The costs of hiring, training, support, salaries, benefits and even the retirement of people are commonly not considered when dealing with detection technologies. However, they are usually significant.

The logistics needed to keep detection technologies in proper operating condition can be as “simple” as timely replacement of batteries. They can be as complicated as repairing a complex instrument with the proper components. Recalibration of instruments, either in the field or after return to a central facility, is another aspect of their proper use. The costs of the acquisition of the needed supplies, their shipment and storage, and their timely delivery to the operators in the field must be taken into account.

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